ANL/ESD/13-XX

Novel Process to Use Vehicle Simulations Directly as Inputs to the VOLPE Model

Energy Systems Division

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Novel Process to Use Vehicle Simulations Directly as Inputs to the VOLPE Model

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1. Introduction

The U.S. Department of Transportation's (DOT) National Highway Traffic Safety Administration (DOT/NHTSA), in coordination with the U.S. Environmental Protection Agency (EPA), recently finalized the nation's first fuel economy standards for medium- and heavy-duty (MDHD) vehicles, and issued a joint final rulemaking to establish Corporate Average Fuel Economy (CAFE) and Greenhouse Gas (GHG) emission standards for model year (MY) 2017–2021 passenger cars and light trucks. DOT/NHTSA's CAFE standards were established pursuant to the amendments made by the Energy Independence and Security Act (EISA) of 2007 to the Energy Policy and Conservation Act (EPCA). Now DOT/NHTSA set tentative standards for model years 2022–2025. In completing these rulemakings, NHTSA has also identified a range of planned future efforts and milestones associated with continuing to meet fuel-economy-related requirements of the Energy Policy and Conservation Act (EPCA) of 1975 and the Energy Independence and Security Act (EISA) of 2007.

The Volpe Center provides analytical support for NHTSA's regulatory and analytical activities related to fuel economy. In developing the standards, DOT/NHTSA made use of the CAFE Compliance and Effects Modeling System (the "Volpe model" or the "CAFE model"), which was developed by DOT's Volpe National Transportation Systems Center for the 2005-2007 CAFE rulemaking and continuously updated since the model is the primary tool used by the agency to evaluate potential CAFE stringency levels by applying technologies incrementally to each manufacturer's fleet until the requirements under consideration are met. The Volpe model relies on numerous technology-related and economic inputs such as a market forecasts, technology cost, and effectiveness estimates; these inputs are categorized by vehicle classification, technology synergies, phase-in rates, cost learning curve adjustments, and technology "decision trees". The Volpe Center assists NHTSA in the development of the engineering and economic inputs to the Volpe model by analyzing the application of potential technologies to the current automotive industry vehicle fleet to determine the feasibility of future CAFE standards and the associated costs and benefits of the standards.

Part of the model's function is to estimate CAFE improvements that a given manufacturer could achieve by applying additional technology to specific vehicles in its product line. To inform decisions regarding the design of specific vehicles, manufacturers may apply techniques such as vehicle and component testing, combustion simulation, powertrain simulation, computational fluid dynamics (CFD) simulation, and full vehicle simulation. Because CAFE standards apply to the average fuel economy across manufacturers' entire fleets of new passenger cars and light trucks, the model, when simulating manufacturers' potential application of technology, considers the entire range of each manufacturer's product line. This typically involves accounting for more than 1,000 distinct vehicle models and variants, many more than can be practically examined using full vehicle simulation (or the other techniques mentioned above). Instead, the model uses estimates of the effectiveness of specific technologies, and arranges technologies in decision trees defining logical progressions from lower to higher levels of cost, complexity, development requirements, and/or implementation challenges.

DOT/NHTSA has made use of vehicle simulation results to update technology effectiveness estimates used by the model. In recent rulemakings, the decision trees have been expanded so that DOT/NHTSA is better able to track the incremental and net/cumulative cost and effectiveness associated with each technology, which substantially improves the "accounting" of costs and effectiveness for CAFE rulemakings. A detailed description of the Volpe model can be found in NHTSA's Final Regulatory Impact Analysis (FRIA) supporting the 2012 rule establishing CAFE standards applicable beginning MY 2017. The FRIA and all other rulemaking documents, the model, source code, model documentation, and all model inputs and outputs are available at http://www.nhtsa.gov/fuel-economy.

A significant number of inputs to Volpe's decision tree model are related to the effectiveness (fuel consumption reduction) for each fuel-saving technology and the combination of several fuel-saving technologies (synergy factors). The effectiveness estimates and synergy factors have come under increased scrutiny over the past several rulemakings. The automotive industry, other government agencies, and non-governmental organizations (NGOs) have been comparing the effectiveness estimates, synergy factors, and CAFE model outputs to estimates and results obtained from physics-based full vehicle simulation tools (software programs). One of the most challenging aspect of the current process remains the selection and definition of the synergy factors which can introduce significant uncertainties. As a result, in a report to NHTSA, the National Academies of Sciences (NAS) recommended that NHTSA use full vehicle simulations tools to develop effectiveness estimates and synergy factors. Full vehicle simulation tools use physics-based mathematical equations, engineering characteristics (e.g., including engine maps, transmission shift points, hybrid vehicle control strategy), and explicit drive cycles to predict the effectiveness of individual fuel-saving technologies and the effectiveness of combinations of fuel-saving technologies.

Argonne National Laboratory (Argonne), a Department of Energy (DOE) national laboratory, has developed a full vehicle simulation tool named Autonomie. Autonomie has become one of the industry's standard tools for analyzing vehicle energy consumption and technology effectiveness.

The objective of this project is to develop and demonstrate a process that replaces both the decision trees and synergy factors by inputs provided directly from a vehicle simulation tool. The report provides a description of the process that was developed by Argonne National Labs and implemented in Autonomie.

2. Problematic

The VOLPE model currently relies on multiple decision trees to represent component technology options, including:

- Powertrain Electrification
- Engine
- Transmission
- Light weighting
- Aerodynamics
- Rolling Resistance

Figure 1 shows an example of the vehicle electrification decision tree. During the simulation, the VOLPE model walks through each decision tree to find the technology that should be selected next to provide the best fuel energy improvement at the lowest cost.

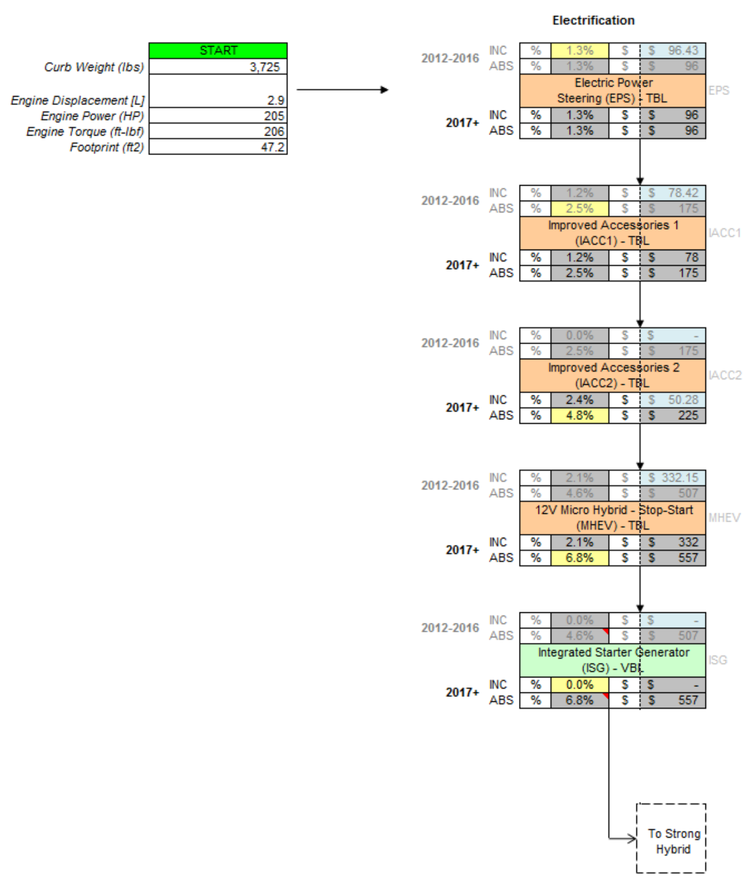


Figure 1 –Hybrid Technology Decision Tree

Figure 2 shows the final decision trees selected equivalent to the number of technology combinations adapted best to represent current and future potential technologies.

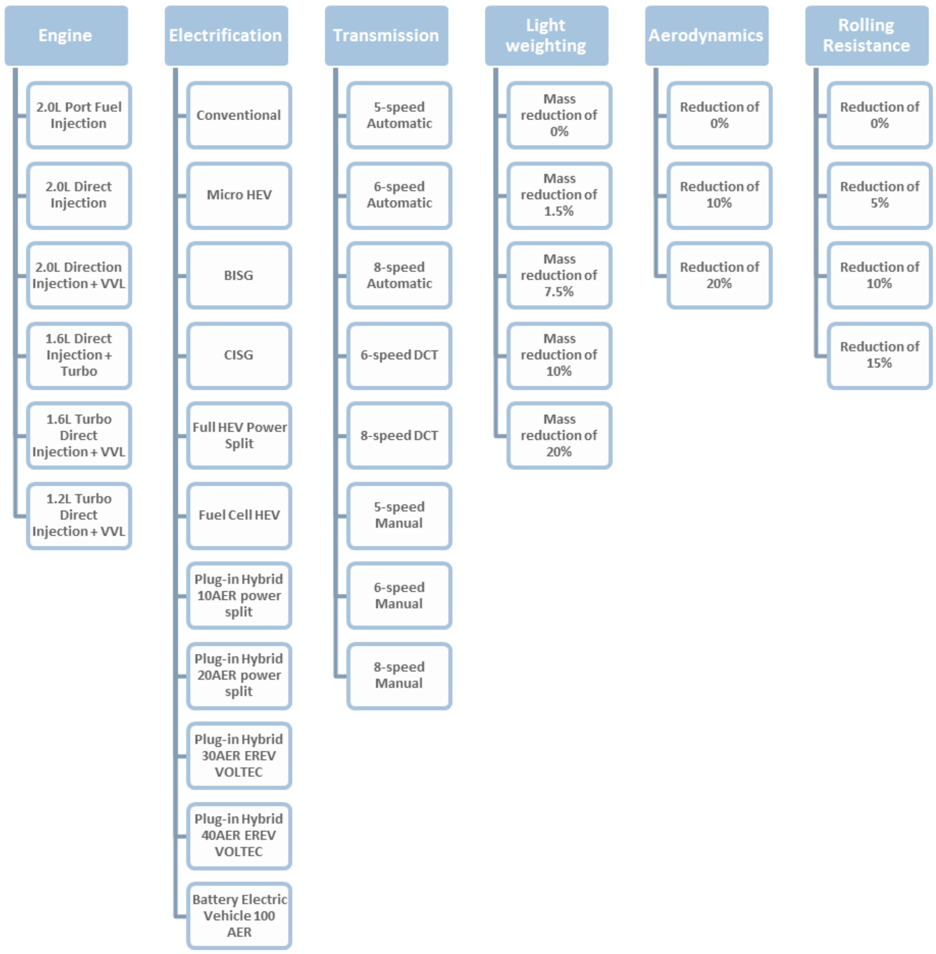


Figure 2 – All Technological Decision Trees

In addition to the numerous decision trees, the VOLPE model currently relies on synergies between technologies. This aspect of the model is critical as multiple technologies can address the same inefficiencies of the component. For example, if an engine technology provides 5% fuel consumption improvement and an advanced transmission 4%, the combination of both technologies will not provide 9%. Developing the relationships between multiple component technologies is challenging, but quantifying it is even more difficult, especially when more than one technology is involved.

3. Process Overview

The main objective is to replace both the decision trees and synergy factors by individual vehicle simulations as shown in Figure 3.

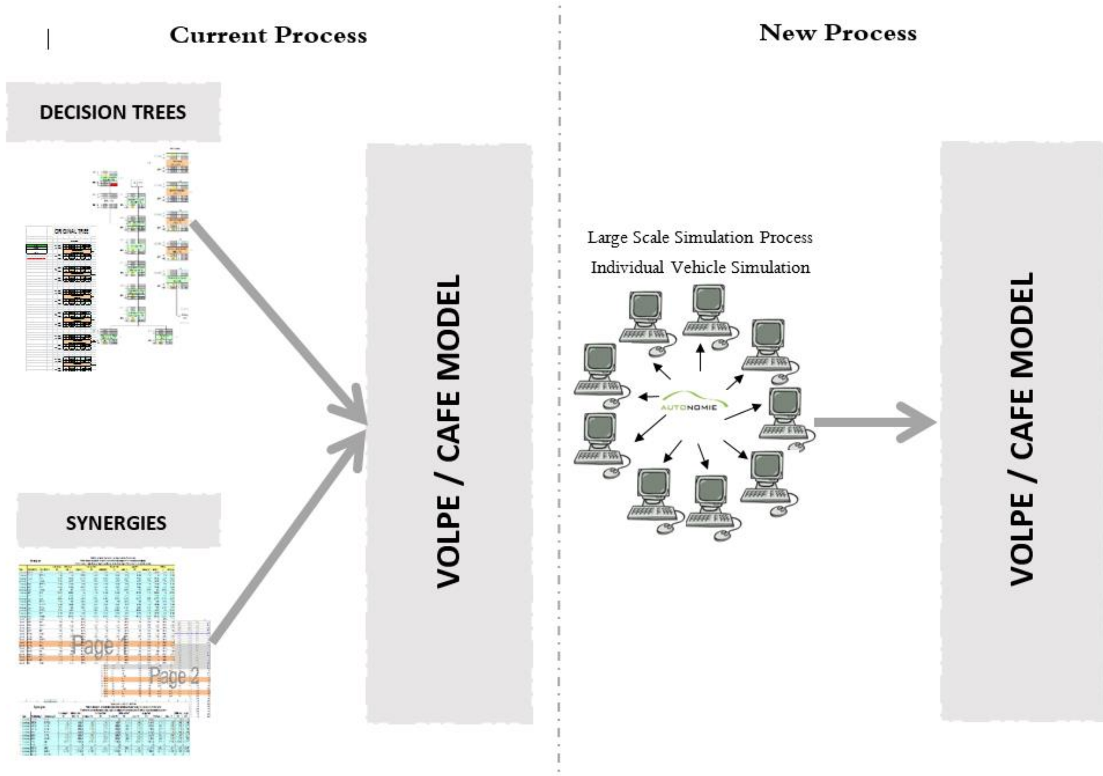


Figure 3 – Replacing Decision Trees and Synergies by Individual Simulations

To do so, individual vehicles have to be simulated to represent every combination of vehicle, powertrain and component technologies. The current decisions trees includes:

- 5 vehicles Classes (Compact, Midsize, Small SUV, Midsize SUV, Pickup)
- 17 engine technologies
- 11 electrification levels (Conventional equivalent to no electrification level)
- 8 transmissions technologies (applied to Low Electrification Level Vehicles only)
- 5 Light Weighting levels
- 4 Rolling Resistance levels
- 3 Aerodynamics levels

For one vehicle class:

4 Low Electrification Level Vehicles x 17 Engines Levels x 8 Transmissions Levels x 5 Light-Weighting Levels x 4 Rolling Resistance Levels x 3 Aerodynamics Levels = 32,640 vehicle

+

<u>7 hybridized vehicles</u>: 5 light weighting x 4 rolling resistance x 3 aerodynamics = 420 vehicles

=

33,060 vehicles for each vehicle class

The result of the trees selections lead to 33,060 simulations for a single vehicle class (or 165,300 for 5) in order to feed the Volpe Model accurately.

The process developed includes the following steps as shown in Figure 4:

- Collect / develop all the technology assumptions
- Develop a process to automatically create the vehicle models
- Size the individual vehicles to meet the same Vehicle Technical Specifications (VTS)
- Run each individual vehicle model on the standard driving cycles
- Create a database with all the required input for the VOLPE model
- Create post-processing tool to validate the database content

Since this process has to be performed in an acceptable amount of time, several additional processes were developed and implemented:

- Use of distributed computing for vehicle sizing and simulation
- Use of statistical analysis to minimize the number of simulations that need to be performed

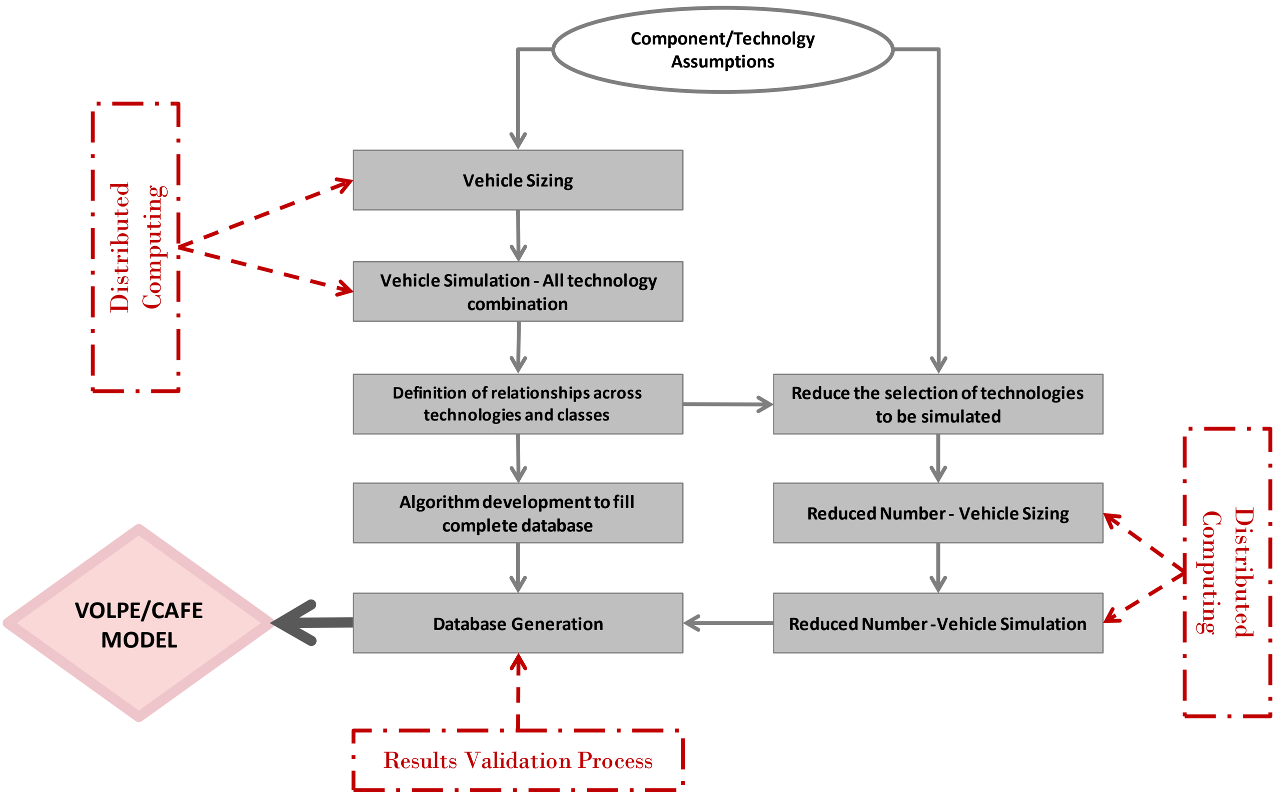


Figure 4 – Large Scale Simulation Process Overview

The following sections of the report will describe each step in details

4. Autonomie

Autonomie is a MATLAB©-based software environment and framework for automotive control-system design, simulation, and analysis. The tool, sponsored by the U.S Department of Energy Vehicle Technologies Office (VTO), is designed for rapid and easy integration of models with varying levels of detail (low to high fidelity) and abstraction (from subsystems to systems and entire architectures), as well as processes (calibration, validation, etc.). Developed by Argonne in collaboration with General Motors, Autonomie was designed to serve as a single tool that can be used to meet the requirements of automotive engineers throughout the development process from modeling to control. Autonomie was built to:

- Support proper methods, from model-in-the-loop, software-in-the-loop, and hardware-in-the-loop to rapid-control-prototyping;
- Integrate math-based engineering activities through all stages of development, from feasibility studies to production release;
- Promote re-use and exchange of models industry-wide through its modeling architecture and framework;
- Support users' customization of the entire software package, including system architecture, processes, and post-processing;
- Mix and match models of different levels of abstraction for execution efficiency with higher-fidelity models where analysis and high-detail understanding is critical;
- Link with commercial off-the-shelf software applications, including GT-Power©, AMESim©, and CarSim©, for detailed, physically based models;
- Provide configuration and database management; and
- Protect proprietary models and processes.

By building models automatically, Autonomie allows the simulation of a very large number of component technologies and powertrain configurations. Autonomie can

- Simulate subsystems, systems, or entire vehicles;
- Predict and analyze fuel efficiency and performance;
- Perform analyses and tests for virtual calibration, verification, and validation of hardware models and algorithms;

- Support system hardware and software requirements;
- Link to optimization algorithms; and
- Supply libraries of models for propulsion architectures of conventional powertrains as well as electric-drive vehicles.

Autonomie will be used in the study to assess the energy consumption of advanced powertrain technologies. Autonomie has been validated for several powertrain configurations and vehicle classes using vehicle test data from Argonne's Advanced Powertrain Research Facility (APRF). This is important for purposes of the current study because the use of validated plant models, vehicle controls and complete vehicle models is critical to properly evaluating the benefit of any specific technology.

Autonomie also allows users to evaluate the impact of component sizing on fuel consumption for different powertrain technologies, as well as to define the component requirements (power, energy, etc.) to maximize fuel displacement for a specific application. To properly evaluate any powertrain-configuration or component-sizing impact, the vehicle-level control algorithms (e.g., engine on/off logic, component operating-conditions algorithm) are critical, especially for electric drives. Argonne also has extensive experience in developing shifting algorithms for conventional vehicles based on the different component characteristics (e.g., engine fuel rate, gear ratios).

The ability to simulate a large number of powertrain configurations, component technologies, and vehicle-level controls over numerous drive cycles has been used to support a very large number of studies, focusing on fuel efficiency, cost-benefit analysis, or greenhouse gases.

5. Technology Selection

Manufacturers have been considering a very large of technology options to improve vehicle energy consumption. The objective of this phase is to define and collect if necessary the performance assumptions for each individual technology that were in the original VOLPE decision trees.

5.1. Engine

Figure 5 represents a list of incremental technologies that have been modeled using GTPower. Six (6) Engine Technologies are available for the current study.

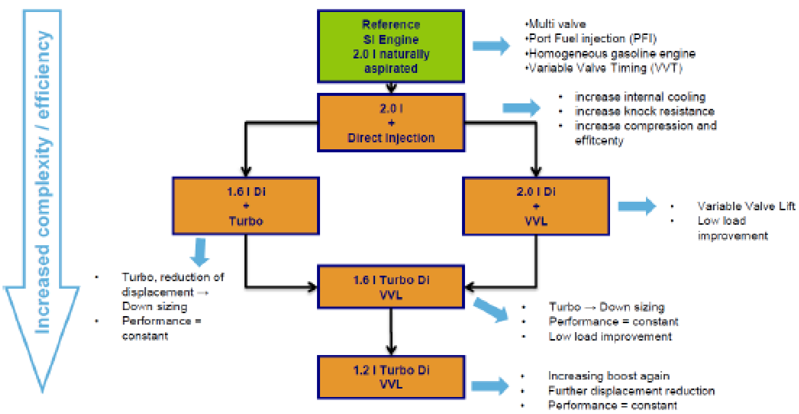


Figure 5 – Current Engine Technologies Considered

Table 1 provides in greater details the technologies and modeling approach for each engine.

Table 1 – Current Engine Technologies Considered

#	label	adopted technology	modeling approach
1	20 PFI	2.0 l naturally aspirated engine, port fuel injection, variable valve timing	
2	20 DI	2.0 l naturally aspirated engine, variable valve timing, raised compression ratio, direct fuel injection,	changing injection, combustion model calculates impact on knock resistance and spark timing
3	20 DI VVL	2.0 l naturally aspirated engine, variable valve timing, raised compression ratio, direct fuel injection, variable valve lift technology	mainly valve lift is scalable, duration too, valve timing adjusted, combustion model calculates impact on knock resistance and spark timing
4	16 T DI	1.6 l turbo charged engine, direct fuel injection, variable valve timing	downsizing displacement, adding turbocharger designed for a 1.6l engine
5	16 T DI VVL	1.6 l turbo charged engine, direct fuel injection, variable valve timing and lift	mainly valve lift is scalable, duration too, valve timing adjusted
6	12 T DI VVL	1.2 l turbo charged engine, decreased displacement, direct fuel injection, variable valve timing and lift	turbocharger and maximal torque output are kept constant (higher BMEP of downsized variant)

Figure 66 shows the original engine decision trees provided by Volpe. It can be noticed that a greater amount of technologies are needed to fulfill meet Volpe's requirement.

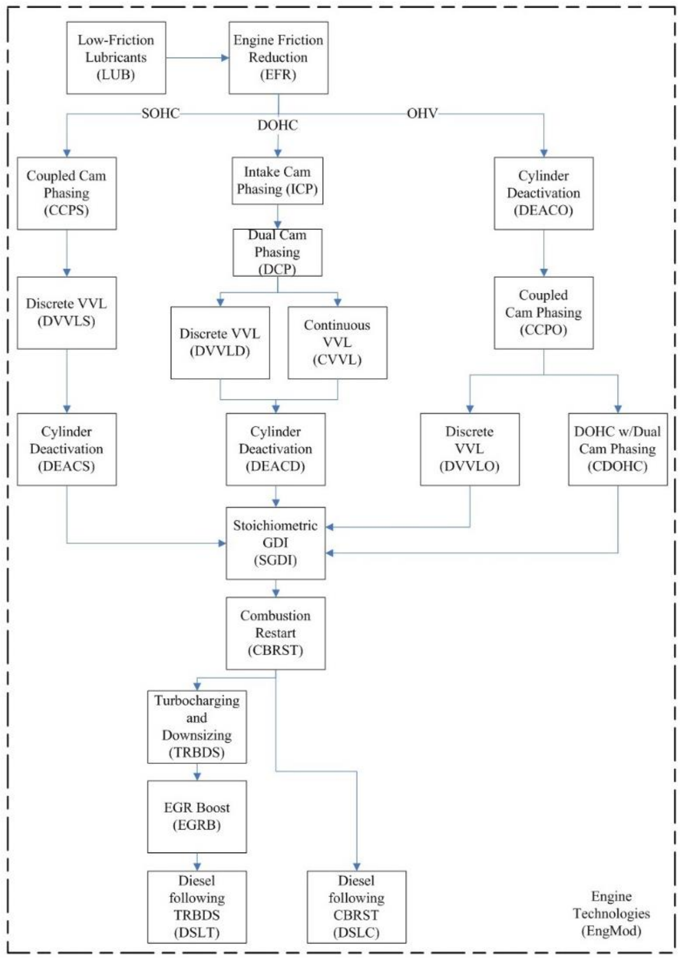


Figure 6 - Original Volpe's Engine Decision Tree

A consulting contract has been finalized for obtaining additional engine maps with more technological breakdown as shown in Figure 7. The contractor will provide wide open throttle (WOT) engine performance values and break specific fuel consumption (BSFC) maps for gasoline engine concepts that might be developed in the future. In order to provide sufficient and realistic results. The contractor will use GT Power models that have been developed and validated with existing dynamometer measurements. The models are trained over the entire engine operating range and will have predictive combustion capability. This is essential, since the BSFC prediction needs to be accurate while the engine setup is subject of change.

The study will provide conclusions about two main factors on the fuel consumption of SI (Spark Ignited) engines. The first factor will be the reduction of pumping losses by adding “low load technology”, such as variable valve lift (VVL) to the engine. Friction is the second parameter to be considered to make an engine more efficient. The mechanical systems required to achieve lower pumping losses can cause more friction. This aspect will be considered by keeping the basic valve control strategy the same, while reducing the friction by simulating a SOHC (Single Overhead Cam) concept instead of a DOHC (Double Overhead Cam) concept. The use of physical models enables such considerations, in some cases regardless of their practical relevance.

The potential of “low load technologies”, downsizing and boosting will be simulated in various steps. In total seventeen (17) variants will be modeled for the next phase of the study. The reference engine will be a 2.0l-4V-I4-PFI engine, which is the starting point for the simulation effort. The reference engine is a roller finger follower concept, which already provides a state-of-the art friction concept.

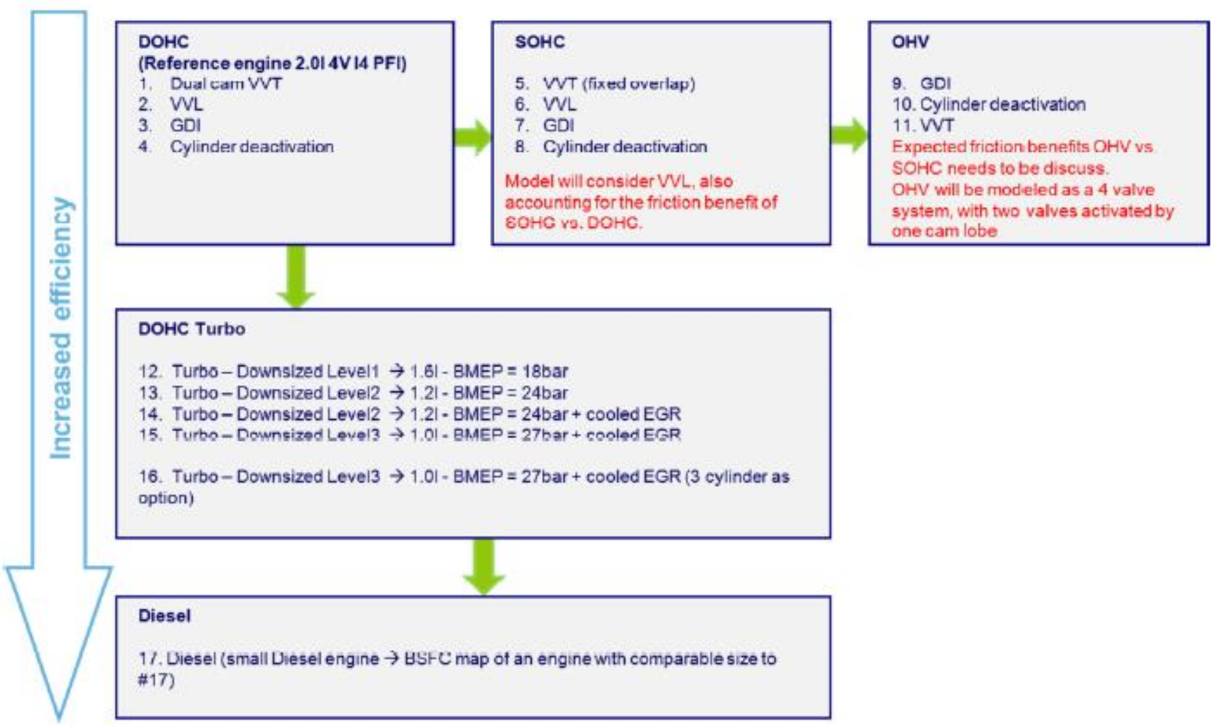


Figure 7 – Future Engine Technologies Considered

5.2. Transmission

To provide more fuel-efficient vehicles to customers, manufacturers have introduced a number of transmission improvements over the past couple of years, including incorporating a higher number of gears and new technologies such as the dual clutch transmission (DCT). Argonne and Volpe agreed on the following selection to best represent the market need:

- 5 speed automatic (Reference Vehicle)
- 6 speed automatic
- 8 speed automatic
- 6 speed DCT
- 8 speed DCT
- CVT
- 5 speed manual
- 6 speed manual
- 8 speed manual

5.3. Light-weighting

Light-weighting will be associated with the glider weight and its secondary effect (such as downsizing) will be taken into account. The glider percentage mass reduction values agreed upon are:

- 0% reduction (Reference Vehicle)
- 1.5% reduction
- 7.5% reduction
- 10% reduction
- 20% reduction

5.4. Rolling resistance

The following rolling resistance reduction values were selected:

- 0% reduction (Reference Vehicle)
- 5% reduction
- 10% reduction
- 15% reduction

5.5. Aerodynamic

The following aerodynamic reduction values were selected:

- 0% reduction (Reference Vehicle)
- 10% reduction
- 20% reduction

5.6. Powertrain Electrification

The selection of hybridization degree and powertrain configuration is complex, since numerous options exist. On the basis of current production vehicles as well as future trends, the following powertrain configurations were selected for the modeling analysis to match Volpe's requests:

- 12-V Micro Hybrid Vehicle (MHEV/start-stop system – no regen.)
- Belt-integrated starter generator (BISG)
- Crank-integrated starter generator (CISG)
- Full Hybrid Electric Vehicle (HEV): single-mode power split configuration with fixed ratio.
- Plug-in Hybrid Vehicle (PHEV10): single-mode power split configuration with fixed ratio with 10-mile AER on the FTP (standard urban) drive cycle.
- Plug-in Hybrid Vehicle (PHEV20): single-mode power split configuration with fixed ratio with 20-mile AER on the FTP (standard urban) drive cycle.
- Plug-in Hybrid Vehicle (PHEV30): VOLTEC EREV configuration with 30-mile AER on the FTP drive cycle
- Plug-in Hybrid Vehicle (PHEV40): VOLTEC EREV configuration with 40-mile AER on the FTP drive cycle
- Fuel-cell Hybrid Electric Vehicle (Fuel-cell HEV): series configuration with 320 miles range on the FTP drive cycle
- Battery Electric Vehicle (BEV): with 100-mile AER on the FTP drive cycle

Note that the AER values are based on unadjusted electrical consumptions. In addition, the belt losses were included for both the MHEV and BISG cases. The pre-transmission parallel configuration was not selected for HEVs and PHEVs because the single mode power split configuration is expected to represent the highest volume of vehicles in the timeframe considered and provide a lower fuel consumption.

6. Vehicle and Component Assumptions

6.1. Reference Vehicle

The objective of the study was to demonstrate the feasibility of the process. As a result, a single vehicle class was selected: midsize vehicle. The reference vehicles used as a starting point are based on conventional powertrains with the specifications summarized below and in Table 22.

Table 2 – Reference Vehicle Main Specifications

Baseline Vehicle Specification	Values
Glider Mass (kg)	1000
Drag coefficient	0.307
Frontal area (m^2)	2.324
Rolling resistance coefficient 1	0.0078
Rolling resistance coefficient 2 (speed term)	0.00012

All the mechanical losses of the components required to run the engine on the dynamometer are included in the engine maps.

6.2. Transmission

The transmission ratios were selected as they represent typical values for high volume vehicles currently on the market. An internal study is currently being performed in order to “optimize” the selection of transmission gear ratios (first gear, middle gear, top gear, and gear span) as a function of the number of gears and transmission technology as well as the engine technology. Future results will experiment transmission design in order to validate this approach on a large number of vehicles and simulations.

Power-split HEVs and PHEV 20 AER both have a planetary gear set with 78 ring teeth and 30 sun teeth, similar to the Toyota Prius. The PHEV 40 AER has a planetary gear set with 83 ring teeth and 37 sun teeth, similar to the GM Voltec.

Fuel Cell vehicles use a two-speed manual transmission to increase the powertrain efficiency as well as allow them to achieve a maximum vehicle speed of at least 100 mph.

BEV vehicles used are fixed gear.

The transmission shifting logic has a significant impact on vehicle fuel economy and should be carefully designed to maximize the powertrain efficiency while maintaining acceptable drive quality. The logic used in the simulated conventional light-duty vehicle models relies on two components:

- The shifting controller, which provides the logic to select the appropriate gear during the simulation; and
- The shifting initializer, the algorithm that defines the shifting maps (i.e., values of the parameters of the shifting controller) specific to a selected set of component assumptions.

Figure 8 shows an example of a complete set of shifting curves for a light-duty vehicle. Two curves of the same color (i.e., upshifting and downshifting curves) never intersect, thus ensuring that there are no shift oscillations, which is important for drivability.

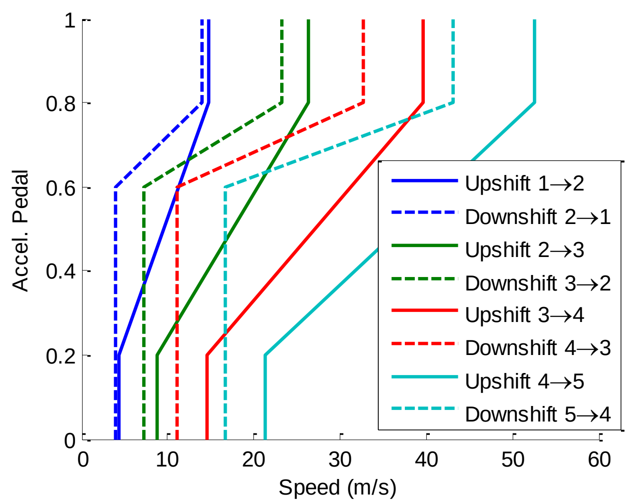


Figure 8 - Shifting Speed Curves for Light-Duty Vehicle in Autonomie

The shifting control algorithm used for the simulation is explained in details in *[Ayman Moawad and Aymeric Rousseau, June 2012, "Impact of Transmission Technology on Fuel Efficiency"]*

The torque converter is modeled as two separate rigid bodies when the coupling is unlocked and as one rigid body when the coupling is locked. The downstream portion of the torque converter unit is treated as being rigidly connected to the drivetrain. Therefore, there is only one degree of dynamic freedom, and the model has only one integrator. This integrator is reset when the coupling is locked, which corresponds to the loss of the degree of dynamic freedom. Figure 9 shows the efficiency of the torque converter used for the study.

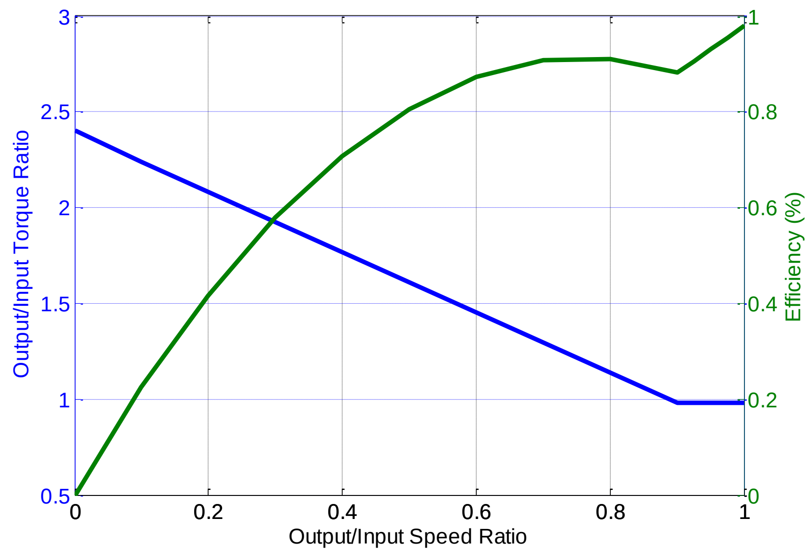


Figure 9 - Torque Converter Efficiency

6.3. Electric Machine

The electric machine performance data (Figure 10 and Figure 11) were provided by Oak Ridge National Laboratory and represent a synchronous permanent-magnet technology. Figure 10 represents the electric machine efficiency map use for the micro HEV, BISG and CISG. Figure 11 represents the efficiency map of the electric machine used for the HEV and PHEVs. The efficiency maps have been developed assuming component normal temperature operating conditions. The electric machine inverter losses are included in the map.

These figures represent the peak torque curves. A constant ratio was assumed between the continuous and peak torque curves:

- 2 for the MHEV, BISG and CISG
- 2 for the Motor 1 and 1.5 for the Motor 2 of the power split HEV and Blended PHEV
- 1 for E-REV, BEVs and Fuel cell HEV

However, due to the drive cycles considered, the electric machines were never limited. Finally, the electric machine specific weight is 1300 W/kg and its controller 10500 W/kg. The peak efficiency is set to 95%.

The main focus of BISG hybrid vehicles is to capture regenerative braking energy as well as provide minimal assist to the engine during high-transient operating modes. As the electric machine is linked to the engine through a belt, its power is usually limited. A value of 7 kW has been used for the BISG.

CISG hybrid vehicles focus on the same areas of improvement as BISG vehicles. However, owing to its position, the electric machine can be larger and consequently, more benefits can be obtained from regenerative braking and assist compared to the BISG vehicle. An electric machine size of 15 kW was selected for the midsize car.

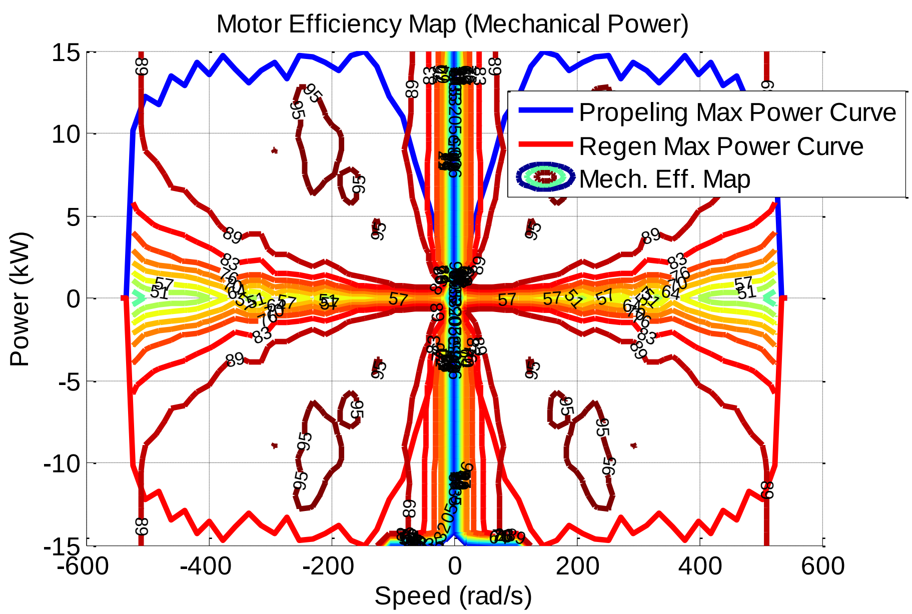


Figure 10 – Electric Machine Map for Micro and Mild HEV

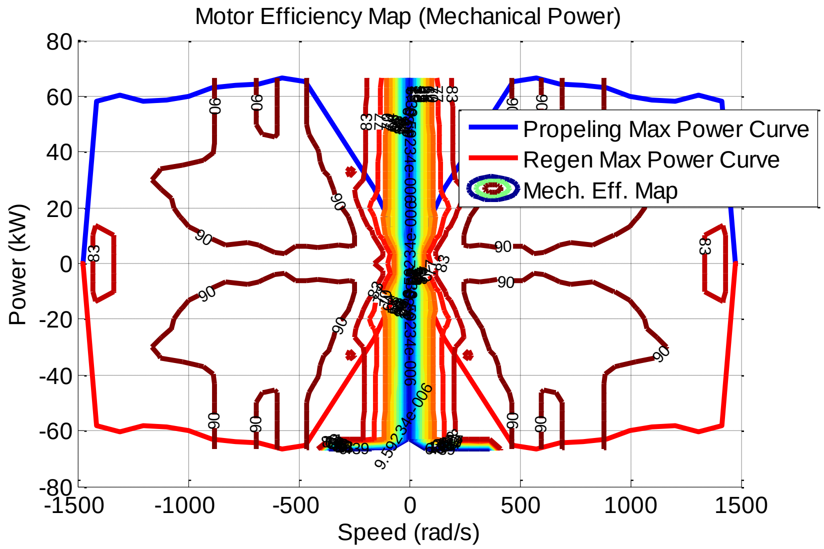


Figure 11 - Electric Machine Map for Full HEV

6.4. Fuel-Cell System

The fuel-cell system was modeled to represent the hydrogen consumption as a function of the produced power. The fuel cell system peak efficiency, including the balance of plant, is 60% and represents normal temperature operating conditions. The data set cannot be provided as it is proprietary. The fuel cell system specific power is 400 W/kg.

The hydrogen storage technology considered is high pressure tank with a specific weight of 0.042 kg H2/kg. As mentioned previously, the tank was sized to provide 320 miles range on the FTP drive cycle.

6.5. Energy Storage System

The battery used for the BISG and CISG HEVs as well as the PHEVs is a lithium-ion battery, as it is assumed that this is the most likely technology to be used. Table 33 provides a summary of the battery characteristics and technologies used by each powertrain.

Table 3 - Description of Reference Battery Characteristics

	Technology	Reference Cell Capacity (Ah)
MHEV	Lead acid	66
BISG	Li-ion	6
CISG	Li-ion	6
HEV	Li-ion	6
PHEVs	Li-ion	41

The battery capacity was selected for each option to allow a global pack voltage between 200V (i.e., full HEV case) and 350V (i.e., BEV case). The energy storage cell weights for the PHEVs are based on 107 Wh/kg for PHEVs 10 and 20AER; 133 Wh/kg for PHEVs 30 and 40 AER and 143 Wh/kg for the BEVs. The energy storage cell weights for MHEV, BISG, CISG and full HEVs are based on 1300 W/kg.

Different useable SOC ranges have also been selected depending on the powertrain configuration:

- 10% SOC range for micro, mild and full HEVs
- 60% SOC range for PHEVs and 70% for BEVs

After a long period of time, batteries lose some of their power and energy capacity. To be able to maintain the same performance at the end of life (EOL) compared to the beginning of life, an oversize factor is applied for both power and energy. These factors are supposed to represent the percentage of power and energy that will not be provided by the battery at the EOL compared to the initial power and energy given by the manufacturer. As for the other components, the performance data used to model the component performances are based on normal temperature operating conditions.

Vehicle test data have shown that, for the drive cycles and test conditions considered, battery cooling does not draw a significant amount of energy if anything at all for most of the vehicle powertrain architectures to the exception of BEVs. In that case, an additional constant power draw was used to take into account battery cooling.

The energy storage system (ESS) block models the battery pack as a charge reservoir and an equivalent circuit. The equivalent circuit accounts for the circuit parameters of the battery pack as if it were a perfect open-circuit voltage source in series with an internal resistance. The amount of charge that the ESS can hold is taken as constant, and the battery is subject to a minimum voltage limit. The amount of charge required to replenish the battery after discharge is affected by coulombic efficiency. A simple single-node thermal model of the battery is implemented with parallel flow air cooling. The voltage is calculated as Vout = Voc – Rint * I with Voc = open circuit voltage, Rint = Internal resistance (two separate set of values for charge and discharge) and I = Internal battery current (accounts for coulombic efficiencies).

6.6. Accessory Loads

Electrical and mechanical accessory base loads were assumed constant over the drive cycles with a value of 220 W. The value, based on measured data from the APRF, is used to represent the average accessory load consumed during the standard urban (FTP) and highway (HFET) drive-cycle testing on a dynamometer. Only the base load accessories are assumed during the simulations, similarly to the dynamometer test procedure.

6.7. Driver

The driver model is based on a look ahead controller. No anticipation is imposed (0 sec anticipated time) during sizing for acceleration test in order to provide realistic vehicle performances.

6.8. Vehicle-Level Control Algorithms

All the vehicle-level control algorithms used in the study have been developed on the basis of vehicle test data collected at the APRF. It is important to note that while the logic for the vehicle-level control algorithms were developed on the basis of test data, only the logic has been used for the present study, since the calibration parameters have been adapted for every specific vehicle to ensure fuel consumption minimization with acceptable drive quality (i.e., acceptable number of engine on/off conditions).

6.8.1. Micro and Mild HEV

The vehicle level control strategies of the micro and mild (i.e., BISG and CISG) vehicles is similar in many aspects due to the low peak power and energy available from the energy storage system.

For the micro HEV case, the engine is turned OFF as soon as the vehicle is fully stopped and restarted as soon as the brake pedal is released. No regenerative braking is considered for that powertrain.

For the mild HEV cases, the engine is turned OFF as soon as the vehicle is fully stopped. However, since some regenerative braking energy is recovered, the vehicle is propelled by the electric machine during vehicle launch allowing the engine to be restarted later.

6.8.2. Single-Mode Power Split HEV

The vehicle-level control strategy of a single-mode power split HEV was based on the Toyota Prius analysis. The control implemented can be divided into three areas: engine-on condition, battery SOC control and engine operating condition. Each algorithm is described below.

Engine-on condition

The operation of the engine determines the mode, such as pure electric vehicle (PEV) mode or HEV mode. The engine is simply turned on when the driver's power demand exceeds a predefined threshold, as shown in Figure 12, the engine is turned on early if the SOC is low, which means that the system is changed from PEV mode to HEV mode to manage the battery SOC.

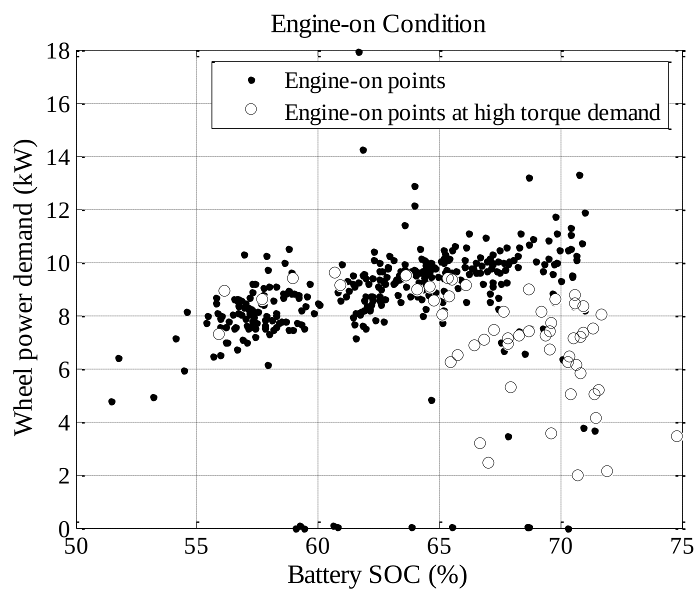


Figure 12 – Engine-On Condition – 2010 Prius Example Based on 25 Test Cycles

The engine is turned off when the vehicle decelerates and is below a certain vehicle speed.

SOC control

The desired output power of the battery is highly related to the energy management strategy. When the vehicle is in HEV mode, the battery power is determined by the current SOC, as shown in Figure 13. The overall trend shows that the energy management strategy tries to bring the SOC back to a regular value of 60%. Both the engine on/off control and the battery power control are robust approaches to manage the SOC in the appropriate range for an input split hybrid. If the SOC is low, the engine is turned on early, and the power split ratio is determined to restore the SOC to 60%, so that the SOC can be safely managed without charge depletion. In summary the battery SOC is controlled by increasing (low SOC) or lowering (high SOC) the engine power demand required to meet the vehicle speed trace.

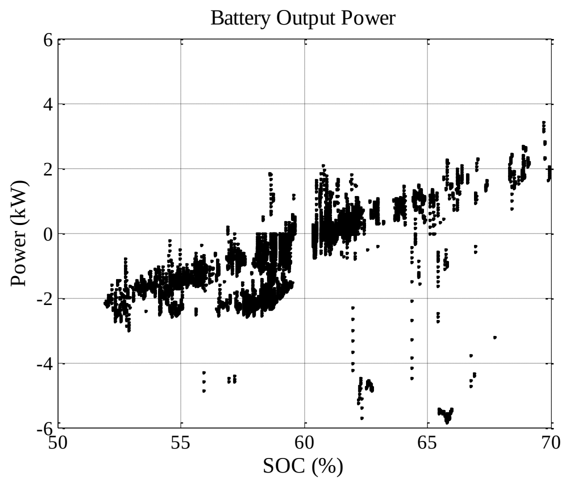


Figure 13 – SOC Regulation Algorithm – 2010 Prius Example Based on 25 Test Cycles

<u>Engine operation</u>

The two previously described control concepts determine the power-split ratio. The concepts do not, however, generate the target speed or torque of the engine because the power-split system could have infinite control targets that produce the same power. Therefore, an additional algorithm is needed to determine the engine speed operating points according to the engine power, as shown in Figure 14. An engine operating line is defined on the basis of the best efficiency curve to select the optimum engine speed for a specific engine power demand.

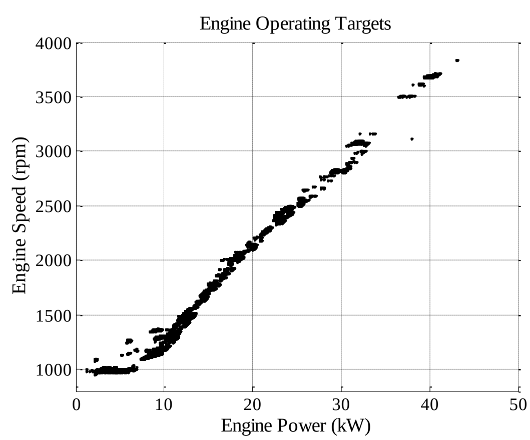


Figure 14 – Example of Engine Operating Target – 2010 Prius Example Based on 25 Test Cycles

In summary, the engine is turned on based on the power demand at the wheel along with the battery SOC. If the engine is turned on, the desired output power of the battery is determined on the basis of the current SOC, and then the engine should provide appropriate power to drive the vehicle. Finally, the engine operating targets are determined by a predefined line, and so the controller can produce required torque values for the motor and the generator on the basis of the engine speed and torque target.

6.8.3. Voltec PHEV

The Voltec system has four different operating modes, as shown in Figure 15.

During EV operation:

- One-motor EV: The single-speed EV drive power-flow, which provides more tractive effort at lower driving speeds.
- Two-motor EV (EV2): The output power-split EV drive power-flow, which has greater efficiency than one-motor EV at higher speeds and lower loads.

During extended-range (ER) operation:

- One-motor ER (Series): The series ER power flow, which provides more tractive effort at lower driving speeds.
- Combined two-motor ER (Split): The output power-split ER power-flow, which has greater efficiency than series at higher speeds and lighter loads.

A vehicle-level control strategy was developed on the basis of vehicle test data to properly select each of the operating modes. The logic developed for the power split mode is similar to the one for the input split configuration discussed previously.

In the EV2 mode- an algorithm has been developed to minimize the losses of both electric machines at every sample time on the basis of each component's efficiency map. For the series mode, the combination of the engine and electric machine losses is also minimized at every sample time. It is important to note that the engine is not operated at its best efficiency point, but rather along its best efficiency line for drive quality and efficiency reasons.

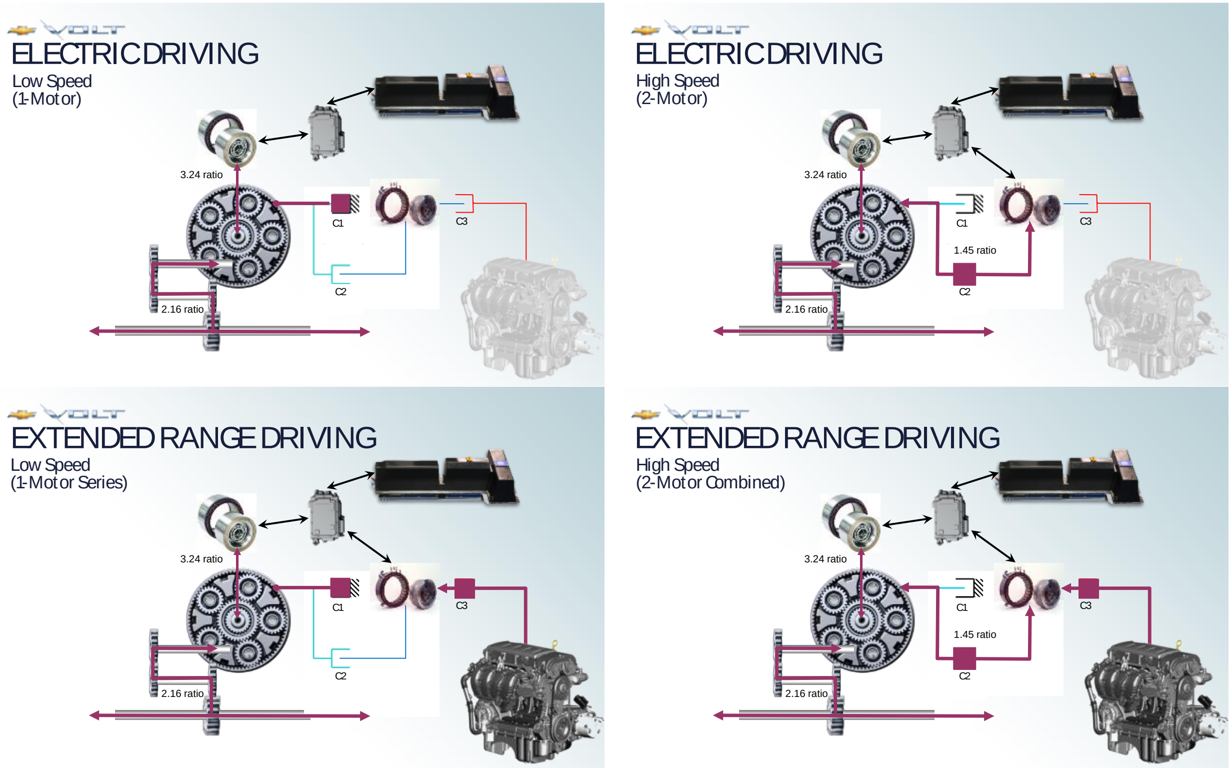


Figure 15 - Voltec Operating Modes [www.gm.com]

6.8.4. Fuel-Cell HEV

Unlike the other vehicle-level controls previously discussed, the algorithm for the fuel-cell HEVs used for the study was not developed on the basis of test data, due to the lack of actual test vehicles. Instead, dynamic programming was used to define the optimum vehicle-level control algorithms for a fuel-cell vehicle. Then, a rule-based control was implemented to represent the rules issued from the dynamic programming. Overall, owing to the high efficiency of the fuel-cell system, the energy storage is only used to recuperate the energy during deceleration and then propel the vehicle under low-load operations. As a result, the fuel-cell system is not used to recharge the battery. Finally, unlike electric drive powertrains with an engine, the battery is not used to smooth the transient demands. An example of fuel-cell hybrid operations is shown in Figure 16.

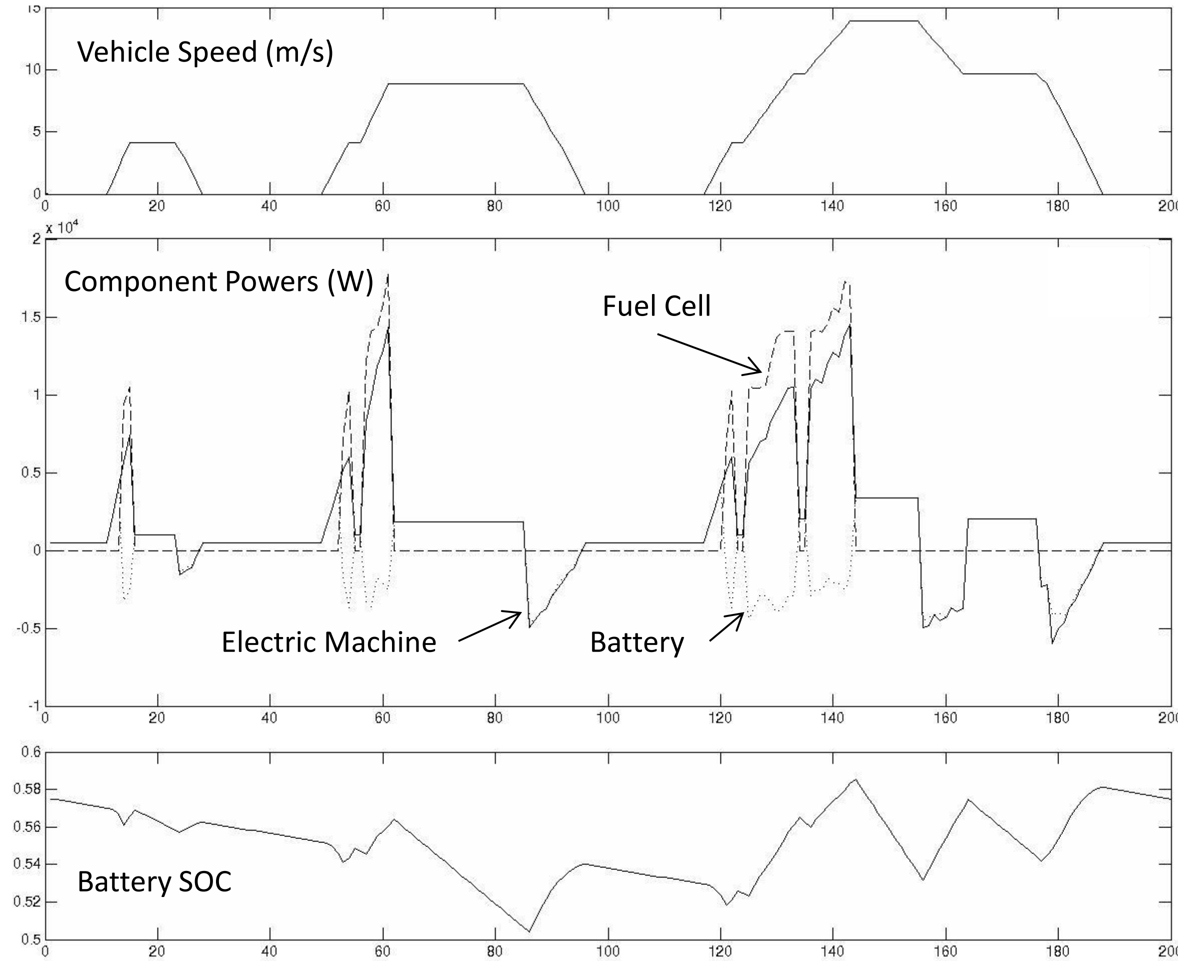


Figure 16 – Component Operating Conditions of a Fuel Cell Vehicle on the Urban European Drive Cycle using Dynamic Programming

6.9. Vehicle Simulation Conditions

All the vehicle simulations were performed under hot conditions (i.e., 20°C ambient temperature with warm components). However, a cold start penalty was applied after the simulations. A cold start penalty of 14% was applied for the fuel consumption of the FTP for conventional vehicles, HEVs and PHEVs; values of 25% and 10% were used for fuel-cell HEVs and BEVs, respectively.

The different simulated test procedures followed the current recommendations of the EPA. The two-cycle test procedure, based on the FTP and HFET drive cycles, was used. Combined values are calculated on the basis of a 55% city and 45% highway cycle, using the standard test procedure. Figure 17 and Figure 18 show the drive cycles used in the simulations.

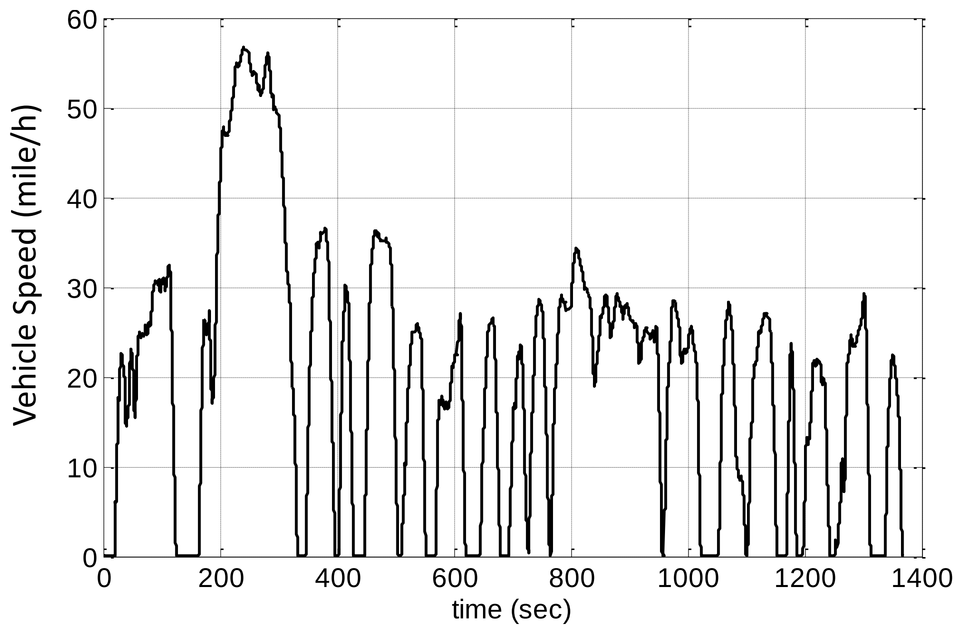


Figure 17 – FTP Drive Cycle

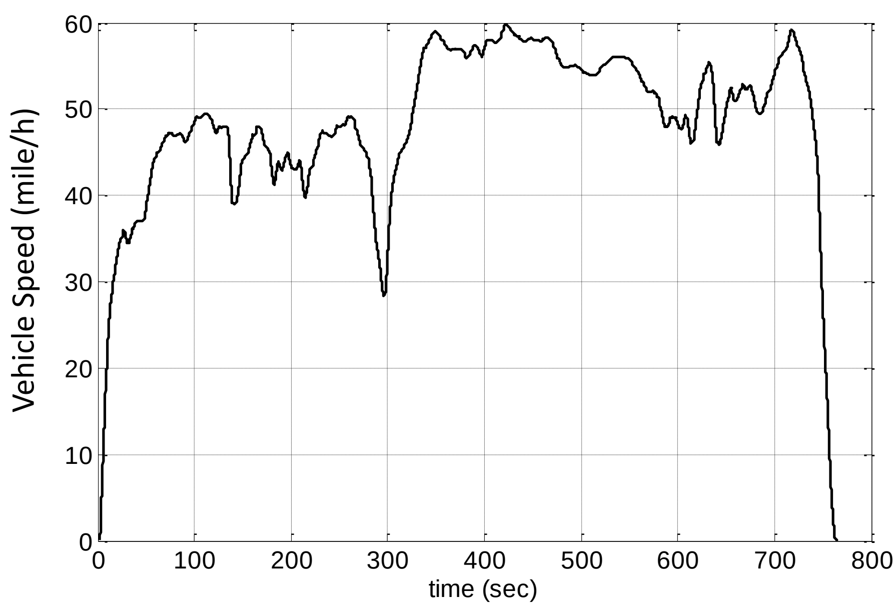


Figure 18 – HFET Drive Cycle

For PHEVs, the SAE J1711 standard procedure was implemented. In 2006 SAE formed a task force committee to revise SAE J1711. The original J1711 covered both HEVs and PHEVs, but the PHEV section was not well developed because at the time of its writing, there was very little PHEV hardware with which to validate the procedures. The new procedures address both blended and EREV types of PHEVs and do so on the basis of test procedure development with real test hardware. SAE J1711 was balloted in 2010 with the title, “Recommended Practice for Measuring the Exhaust Emissions and Fuel Economy of Hybrid-Electric Vehicles, Including Plug-in Hybrid Vehicles.”

For any given test schedule, the J1711 procedure approach is comprised of two separate test procedures. One is the Full Charge Test (FCT), which captures all charge-depleting-mode fuel and electricity consumption results. The other is the Charge-Sustaining Test (CST), which is conducted the same way hybrids have been tested for over a decade. PHEV test procedures also define the steps and requirements for soak and charging for the FCT.

<u>Charge-Depleting Test</u>

The FCT is a series of cycles of the same schedule run in series. The test starts at a full charge and run in charge-depleting (CD) mode until charge-sustaining is observed. See SAE J1711 for more details on the end of test (EOT) criterion and finding the exact point where CD operation transitions to charge-sustaining (CS) operation.

For any given test cycle, the CD mode results can be processes in many different ways. One method is to lump the depleting results and associate the results for the particular range distance of operation from full charge until the transition to CS mode occurs. This requires finding the charge-depleting range, shown in Figure 19 as “Rcda.”

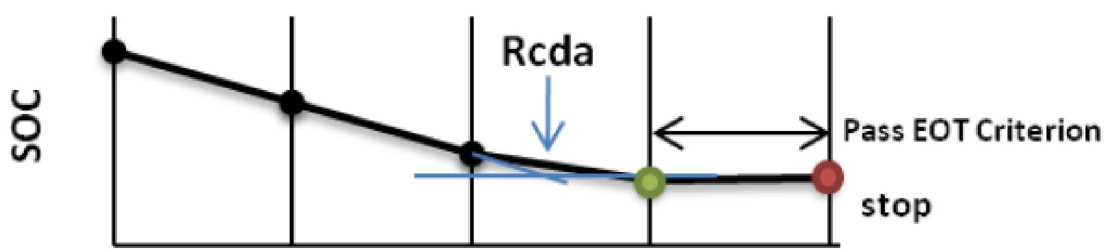


Figure 19 – Representation of Charge Depleting Range Concept

For PHEVs with a blended depleting operation, the CD results include both fuel and electricity consumption. For EREV PHEVs, the equivalent all-electric range (EAER) is calculated (similar but not exactly the Rcda, see California ARB rules for definition of EAER) and then the electric energy consumption is associated with that range distance.

Charge-Sustaining Test

The CST is similar to conventional vehicle testing. The only significant additional requirement is to charge balance during the test. If the net energy change (NEC) is smaller than 1% of the consumed fuel energy, then it is assumed to be charge-balanced. For RESSs comprised of batteries, it is defined as A•h multiplied by the average of the initial and ending voltage.

Combining CD and CS Mode Using Utility Factors (UF)

Comparison of PHEV results with different depleting modes and varying battery capacities is not directly possible. Whereas conventional vehicle fuel use is only mildly dependent upon distance driven, PHEVs have two modes that are entirely dependent upon the distance traveled (energy depleted) between charge events. Average daily distance is not useful because it will not provide information about the proper split between CD and CD modes. What is needed is the actual daily driving distance profile. The 2001 NHTS data was processed in order to calculate a percentage split between CD and CS mode for a given vehicle's CD range. The "Fleet Utility Factor" is shown in Figure 20 below.

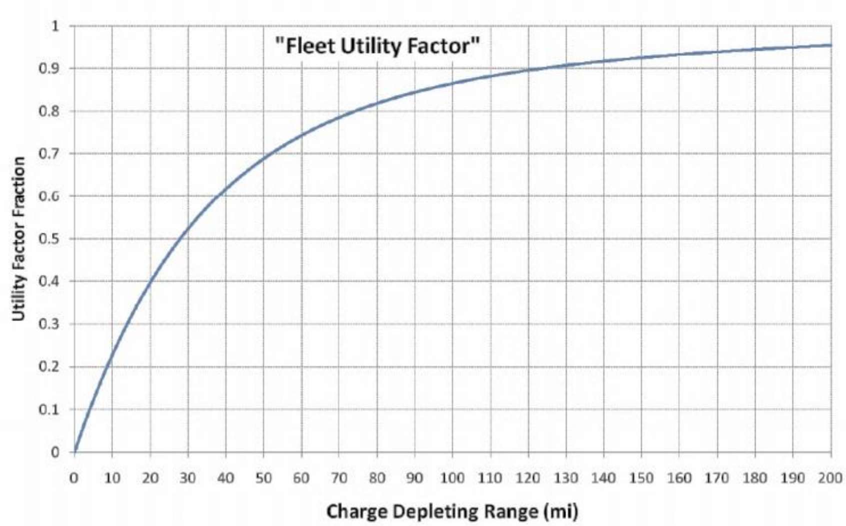


Figure 20 – Fleet Utility Factors

The UF weighted results can be calculated in one of two ways. For any given cycle, the CD range (from the FCT) is found and the lumped CD fuel and electricity consumption rates are weighted with the CS results according to the Fleet UF.

The second UF approach weights the results cycle by cycle. This approach is less prone to calculation anomalies associated with determining CD range. It is also more robust for PHEVs that vary the controls as the battery is being depleted. The approach fractionalizes the UF into weighting factors for each cycle that add up to the total UF for the total distance traveled in all CD cycles tested (different than the estimated CD range). The equation is shown below.

$$Y_{UFW} = \sum_{i=1}^{lastCDcycle} \left[\left(UF(i * D_{cycle}) - UF((i-1) * D_{cycle}) \right) * Y_{CD_i} \right] + \left[1 - UF(R_{CDC}) \right] * Y_{CST}$$

$$E_{UFW} = \sum_{i=1}^{lastCDcycle} \left[\left(UF(i * D_{cycle}) - UF((i-1) * D_{cycle}) \right) * E_{CD_i} \right]$$

Y_{UFW} = Utility Factor weighted fuel consumption, in gal/mi
E_{UFW} = Utility Factor weighted AC electrical energy consumption, in AC Wh/mi
UF(x) = Appropriate Utility Factor fraction at a given distance —x (see Appendix A)
Y_{CDi} = Fuel consumption, in gal/mi, for the —i th test in the FCT
Y_{CST} = Fuel consumption, in gal/mi, for the CST
E_{CDi} = AC electrical energy consumption, in AC W•h/mi, for the —i th test in the FCT

For each vehicle class considered in this study, all the vehicles have been sized to meet the same requirements:

- Initial vehicle movement (IVM) to 60 mph in 9 sec +/-0.1 sec
- Maximum grade (grade ability) of 6% at 65 mph at gross vehicle weight (GVW)
- Maximum vehicle speed >100 mph

These requirements are a good representation of the current American automotive market as well as American drivers' expectations. A relationship between curb weight and GVW was developed on the basis of current technologies to estimate the GVW of future technologies. The component assumptions are described in the following section while the component sizing will be described later in the report.

7. Individual Vehicles Setup Process

The Large Scale Simulation Process has been developed by Argonne in order to run a very large number of vehicles/simulations in a fast and flexible way. It allows Argonne to quickly respond to Volpe's requests.

7.1. Vehicle Spreadsheet Definition

A template spreadsheet containing the basic information of a vehicle such as vehicle name, vehicle class, and vehicle technology; as well as components information such as battery technology, engine technology, transmission type etc… is defined.

The template spreadsheet contains different tabs. In each tab, each column outlines a vehicle configuration. As a result, each spreadsheet contains four (4) columns referring to the four Low Electrification Level Vehicles and eleven (11) columns referring to the eleven High Electrification Level Vehicles. Each spreadsheet has seven (7) tabs – described in the following sections:

- Vehicle Tab
- Parameter Tab
- Control Tab
- Sizing Tab
- Run Tab
- Translation Tab
- Assumptions Tab

7.1.1. Vehicle Tab

The “Vehicle” tab shown in Figure 21 defines the initialization files and the component models required for each vehicle, and the vehicle configuration selected. The selection of different initialization files will depend on the tree selection and the technological combination nominated for that vehicle.

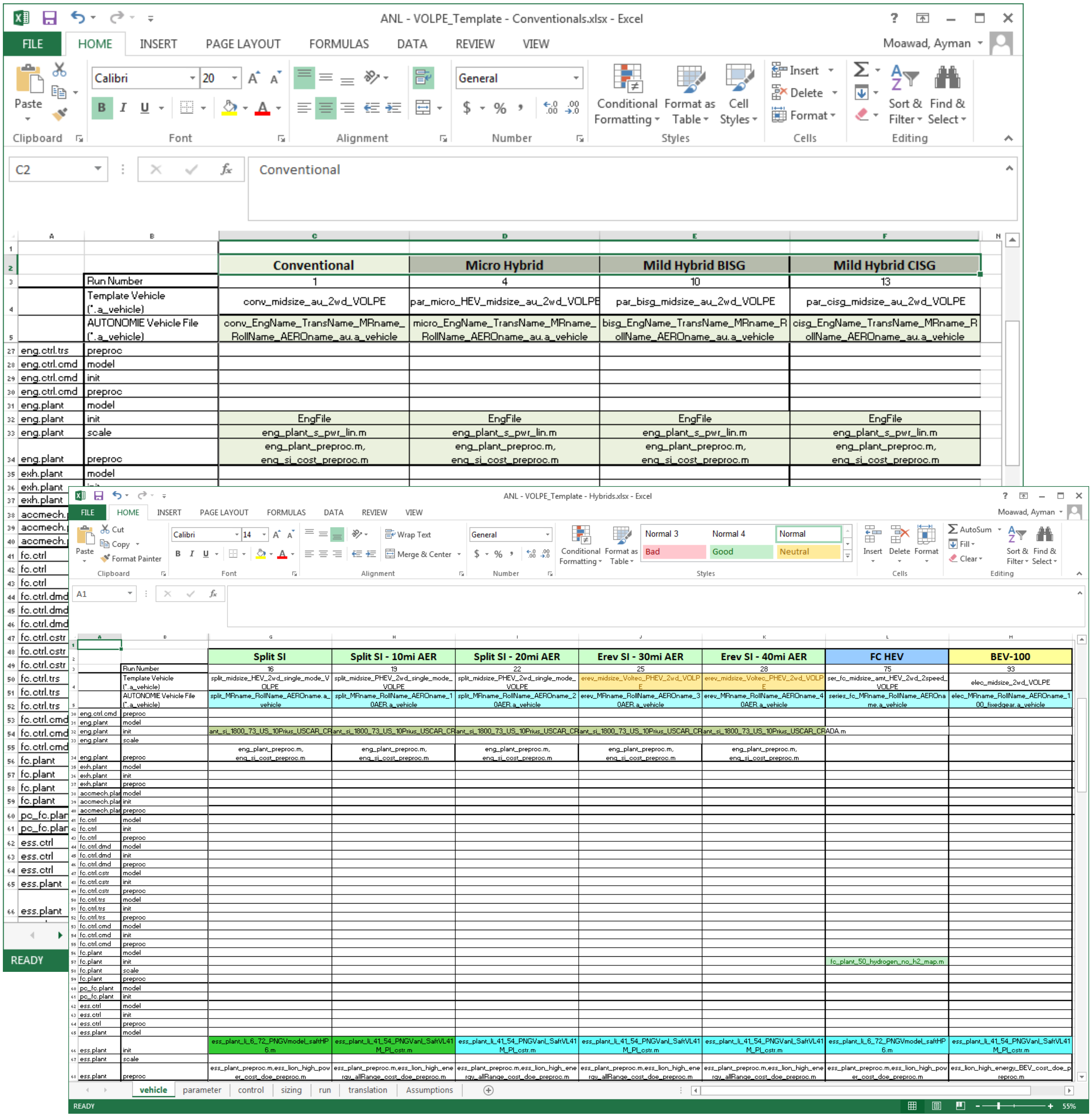


Figure 21 – Vehicle Setup – Vehicle Tab

7.1.2. Parameter Tab

The “Parameter” tab shown in Figure 22 defines the values of the components specific to the vehicle designated (powers, masses, performance constraints, etc…)

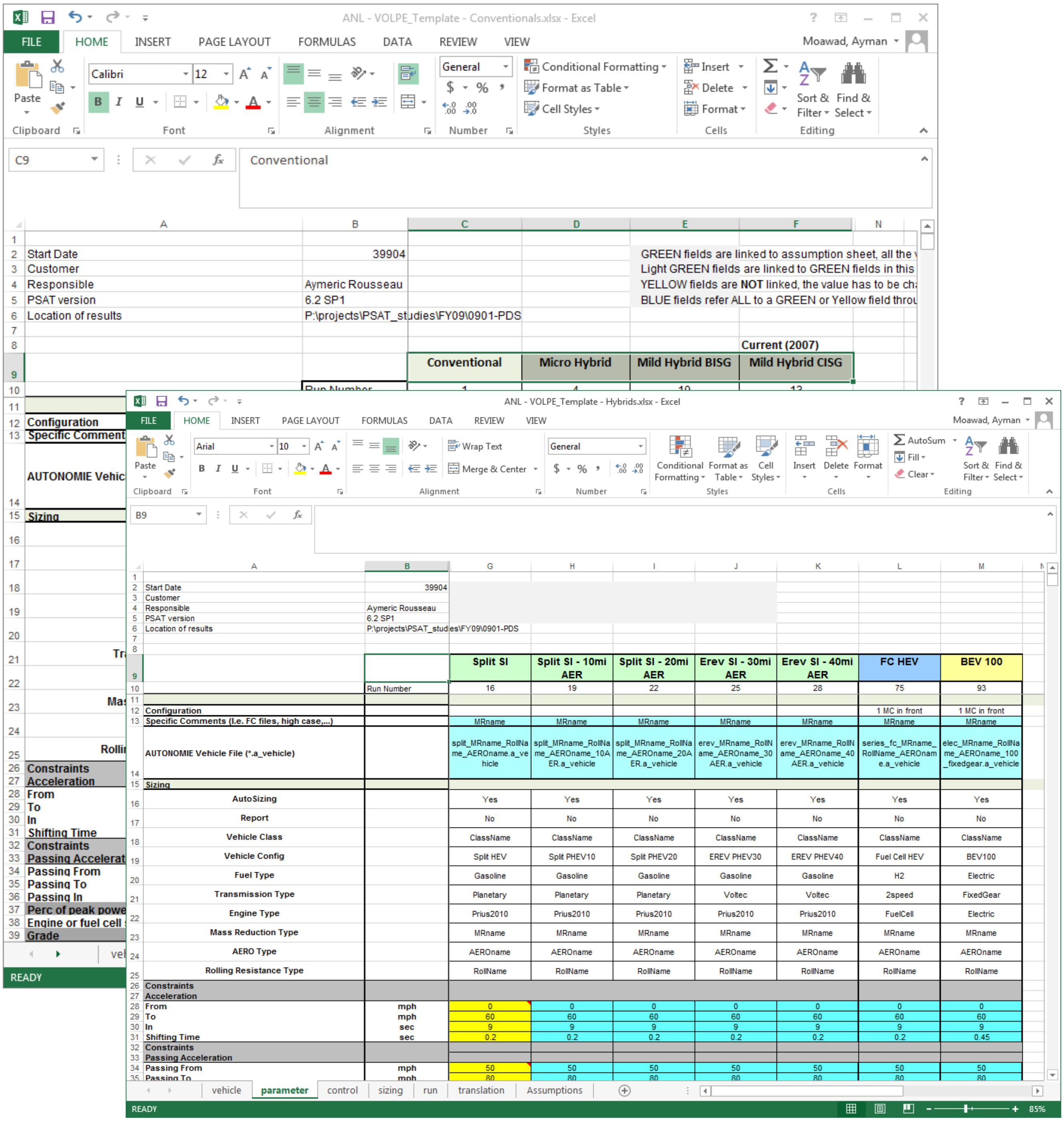


Figure 22 – Vehicle Setup – Parameter Tab

7.1.3. Control Tab

The "Control" tab shown in Figure 23 selects the appropriate controller needed for the designated vehicle

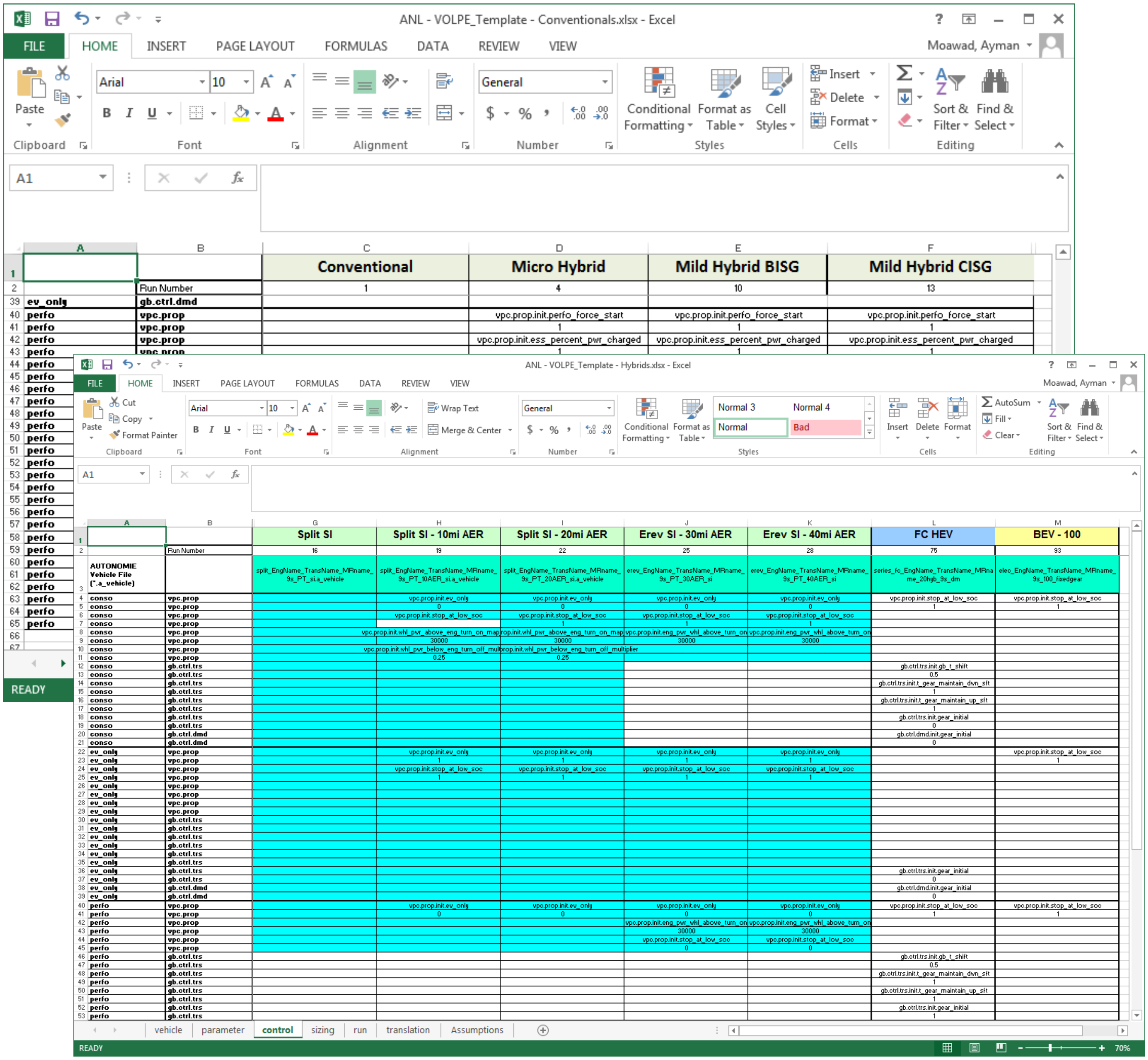


Figure 23 – Vehicle Setup – Control Tab

7.1.4. Sizing Tab

The “Sizing” tab shown in Figure 24 selects the appropriate sizing rule/algorithms to run the vehicle performance test.

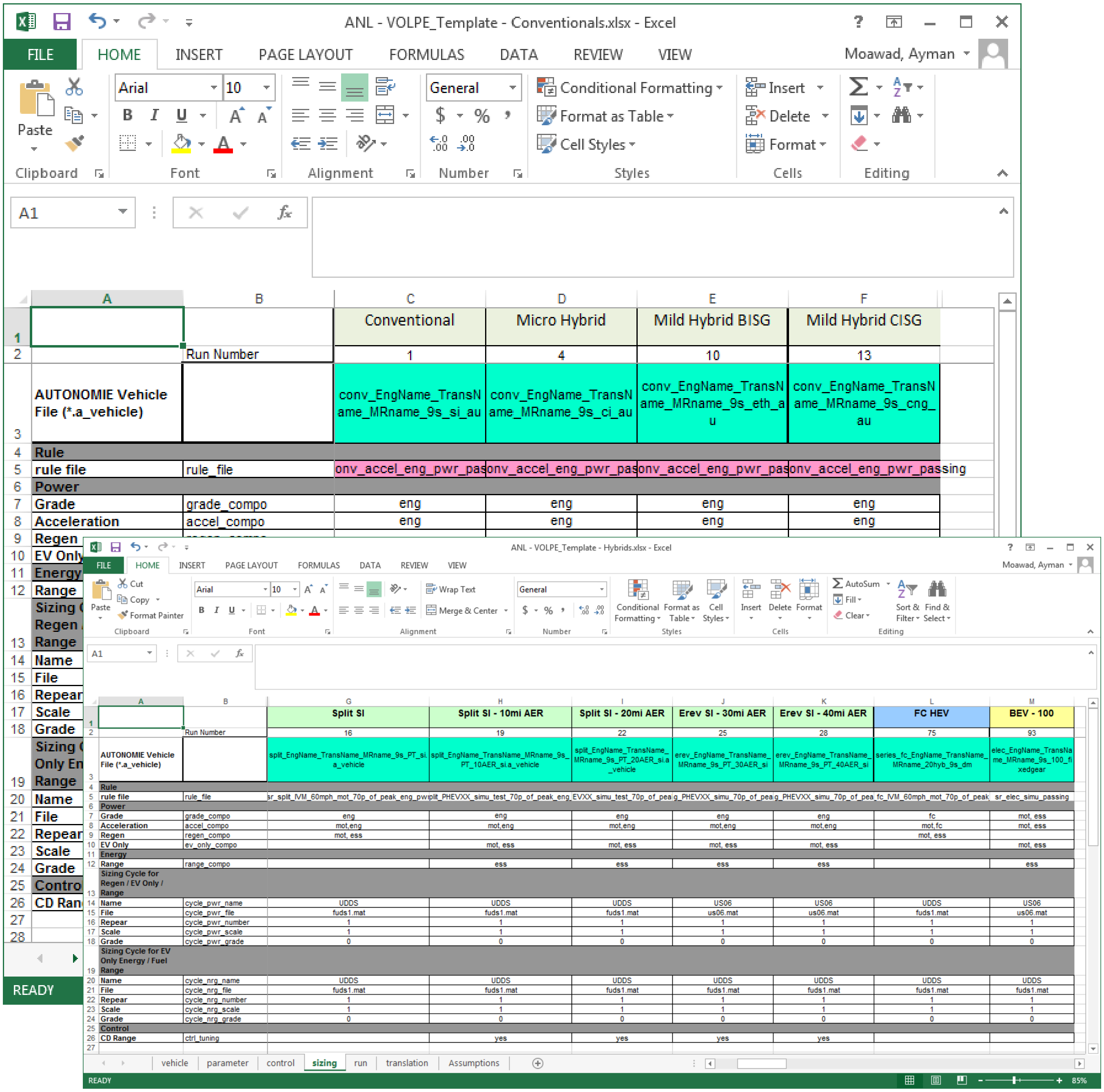


Figure 24 – Vehicle Setup – Sizing Tab

7.1.5. Run Tab

The ‘Run” tab shown in Figure 25 selects the drive cycle/procedure that needs to be run.

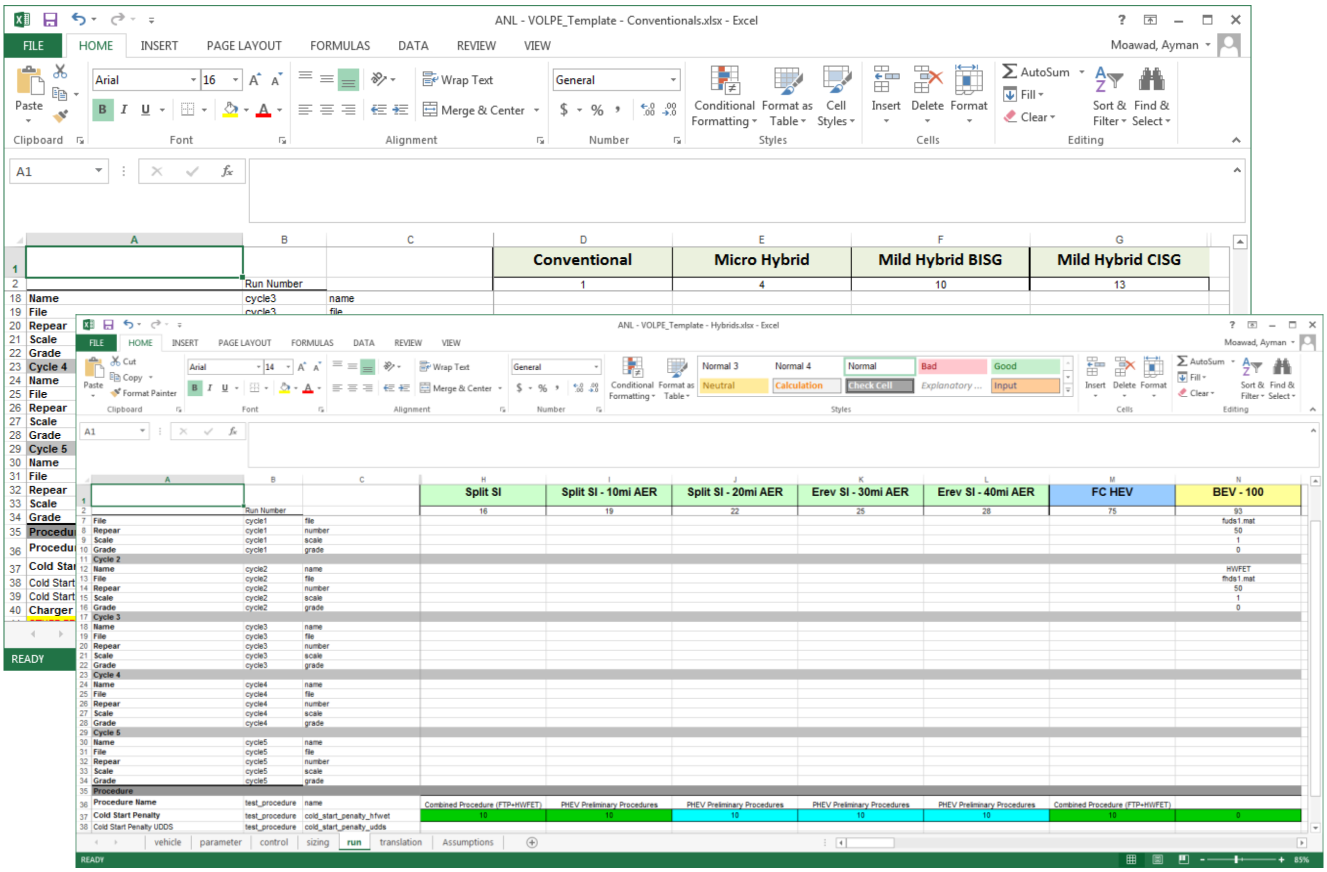
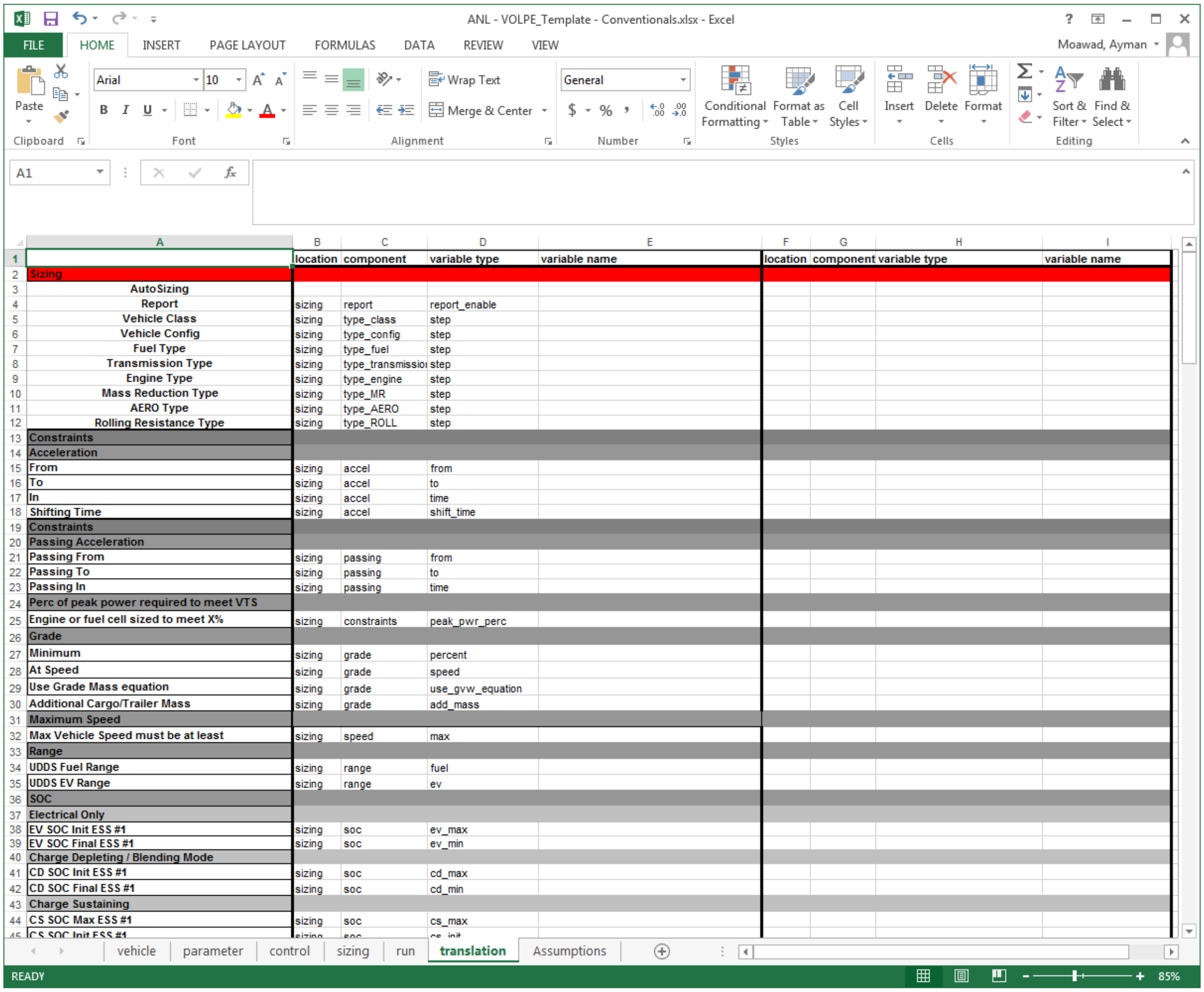


Figure 25 – Vehicle Setup – Run Tab

7.1.6. Translation Tab

The "Translation" tab shown in Figure 26 translates and transfers every input into Autonomie for the vehicle creation.



A	location	component	variable type	variable name	location	component	variable type	variable name
Sizing								
AutoSizing								
Report	sizing	report	report_enable					
Vehicle Class	sizing	type_class	step					
Vehicle Config	sizing	type_config	step					
Fuel Type	sizing	type_fuel	step					
Transmission Type	sizing	type_transmissio	step					
Engine Type	sizing	type_engine	step					
Mass Reduction Type	sizing	type_MR	step					
AERO Type	sizing	type_AERO	step					
Rolling Resistance Type	sizing	type_ROLL	step					
Constraints								
Acceleration								
From	sizing	accel	from					
To	sizing	accel	to					
In	sizing	accel	time					
Shifting Time	sizing	accel	shift_time					
Constraints								
Passing Acceleration								
Passing From	sizing	passing	from					
Passing To	sizing	passing	to					
Passing In	sizing	passing	time					
Perc of peak power required to meet VTS								
Engine or fuel cell sized to meet X%	sizing	constraints	peak_pwr_perc					
Grade								
Minimum	sizing	grade	percent					
At Speed	sizing	grade	speed					
Use Grade Mass equation	sizing	grade	use_gvw_equation					
Additional Cargo/Trailer Mass	sizing	grade	add_mass					
Maximum Speed								
Max Vehicle Speed must be at least	sizing	speed	max					
Range								
UDDS Fuel Range	sizing	range	fuel					
UDDS EV Range	sizing	range	ev					
SOC								
Electrical Only								
EV SOC Init ESS #1	sizing	soc	ev_max					
EV SOC Final ESS #1	sizing	soc	ev_min					
Charge Depleting / Blending Mode								
CD SOC Init ESS #1	sizing	soc	cd_max					
CD SOC Final ESS #1	sizing	soc	cd_min					
Charge Sustaining								
CS SOC Max ESS #1	sizing	soc	cs_max					
CS SOC Init ESS #1	sizing	soc	cs_init					

Figure 26 – Vehicle Setup – Translation Tab

7.1.7. Assumption Tab

The “Assumption” tab shown in Figure 27 describes the vehicle and component assumptions used in the definition of the vehicle.

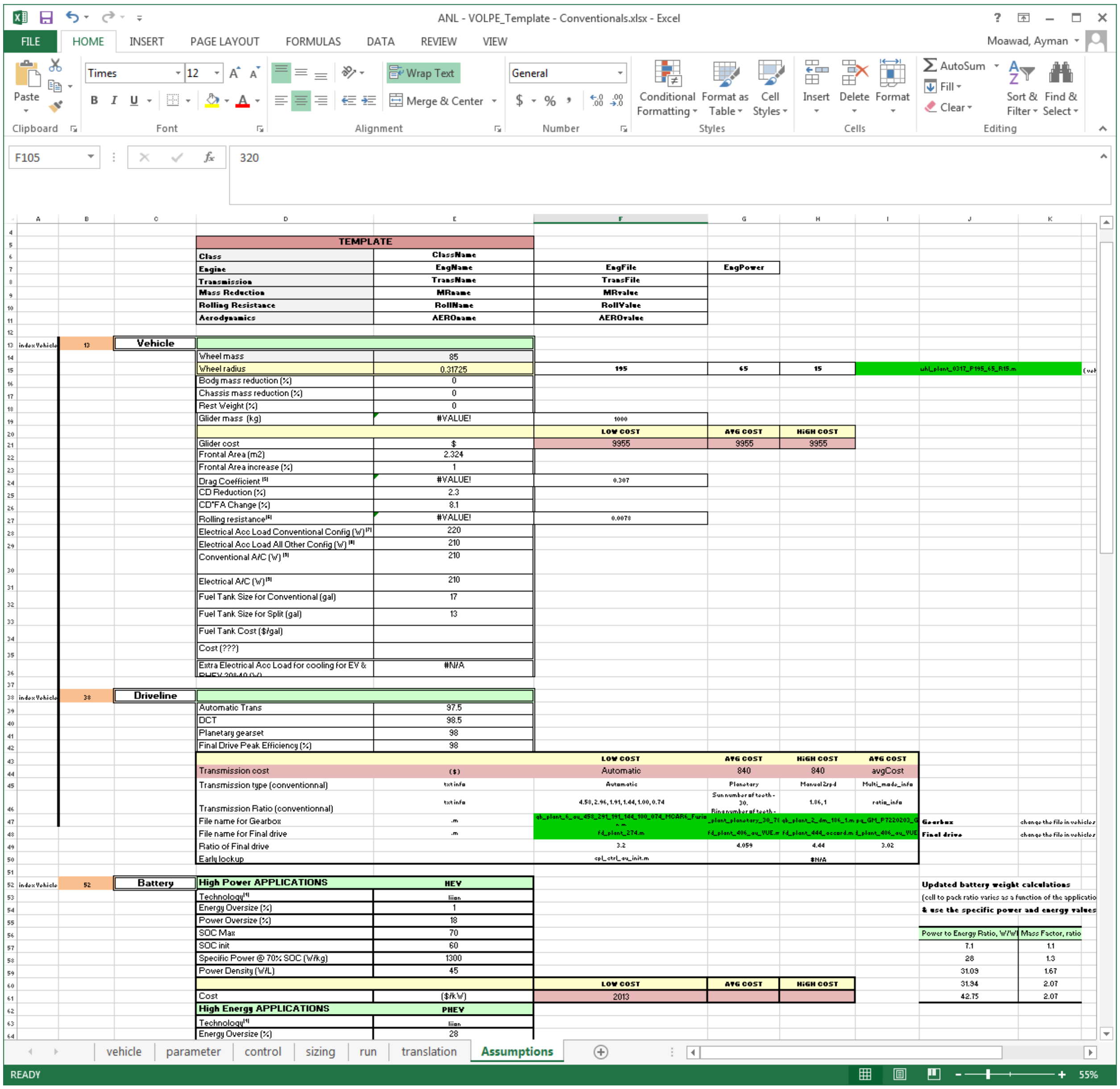


Figure 27 – Vehicle Setup – Assumption Tab

7.2. Multi Spreadsheet Expansion/Duplication

After defining the spreadsheet with all the component and vehicle inputs. A multiplier code, shown in Figure 28, expands the reference/template spreadsheet into as many spreadsheets needed to define all the vehicle's technological combinations based on the decision trees input.

The template spreadsheet is duplicated, multiplied and expanded to define the complete combination tree equivalent to a total of 11,940 vehicle created.

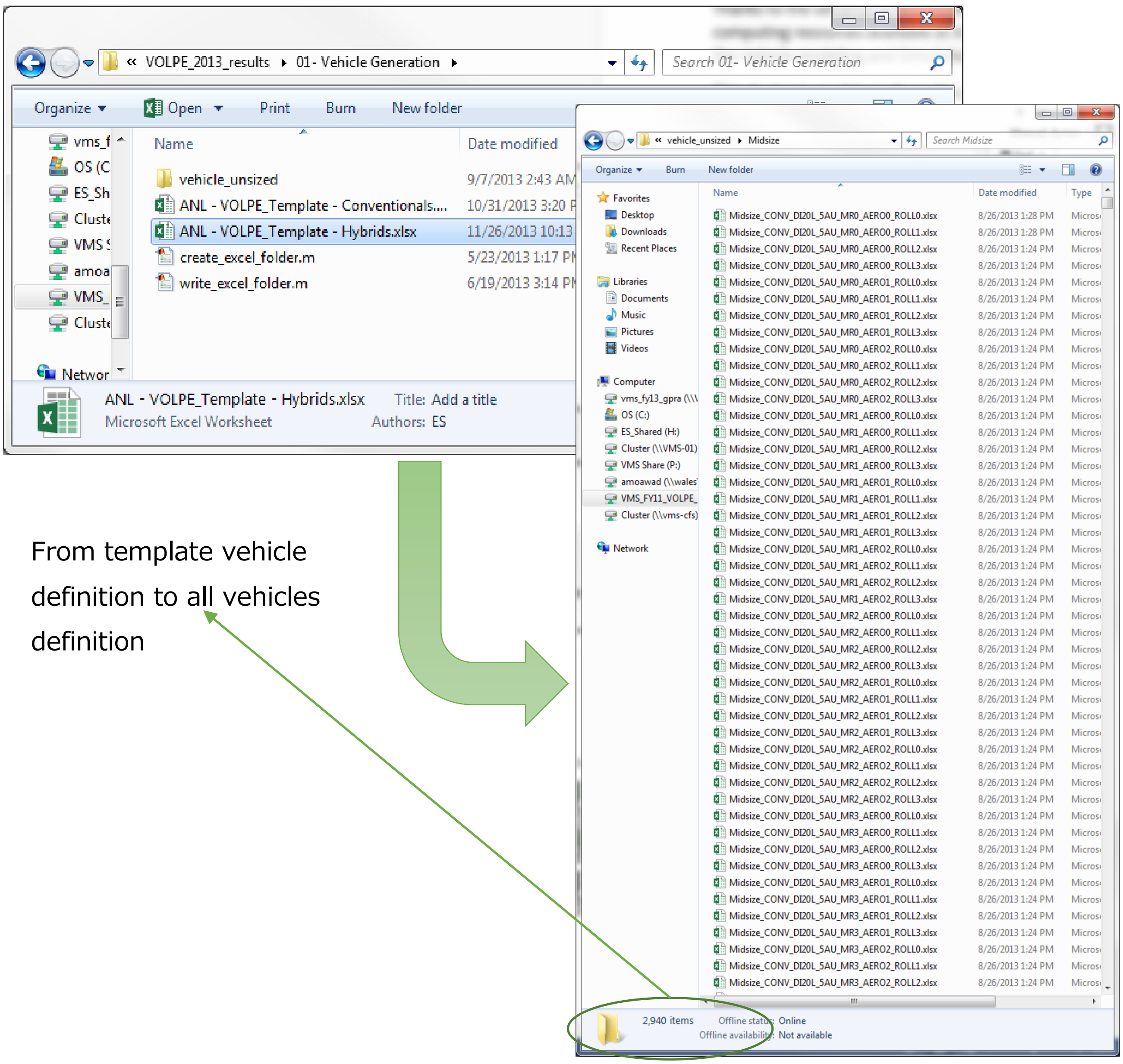


Figure 28 – Multi Spreadsheet Expansion / Duplication

8. Distributed Computing Process

At that stage, all the individual vehicles are created and ready to be sized and simulated in Autonomie. Running 11,940 vehicles requires more than 250,000 simulations from sizing algorithms - imposing recurrence and iteration/looping – to the actual vehicle simulation on cycles and combined or PHEV procedures.

With a very large number of technologies to simulate, usual computing resources is not practical anymore. Running all the simulations on one computer would take several months/years before any analysis could be performed.

Thanks to the advance in distributed computing, simulation time can be greatly reduced. Among all the computing resources available at Argonne National Labs, a cluster of 128 worker nodes is dedicated to the System Modeling and Control group. A larger computing facility could be used in the future to further accelerate the simulations.

8.1. Setup

The workers of the distributed computer use Autonomie as the Simulation Framework and are synchronized by a cluster head node computer. This cluster head node takes the information from the Excel file describing the different technology pathways to simulate and distribute the simulations across the workers.

An algorithm was developed to optimize the distribution of jobs for vehicle simulations and parametric studies. This system was used to run the entire study. As a result, the total simulation time is about 84 hours (3.5 days).

When all the simulation are run, the process automatically generates summary Excel file of the simulation sets. Those simulation details can be reviewed in Autonomie for additional analysis.

Figure 29 shows the distributed computing process diagram.

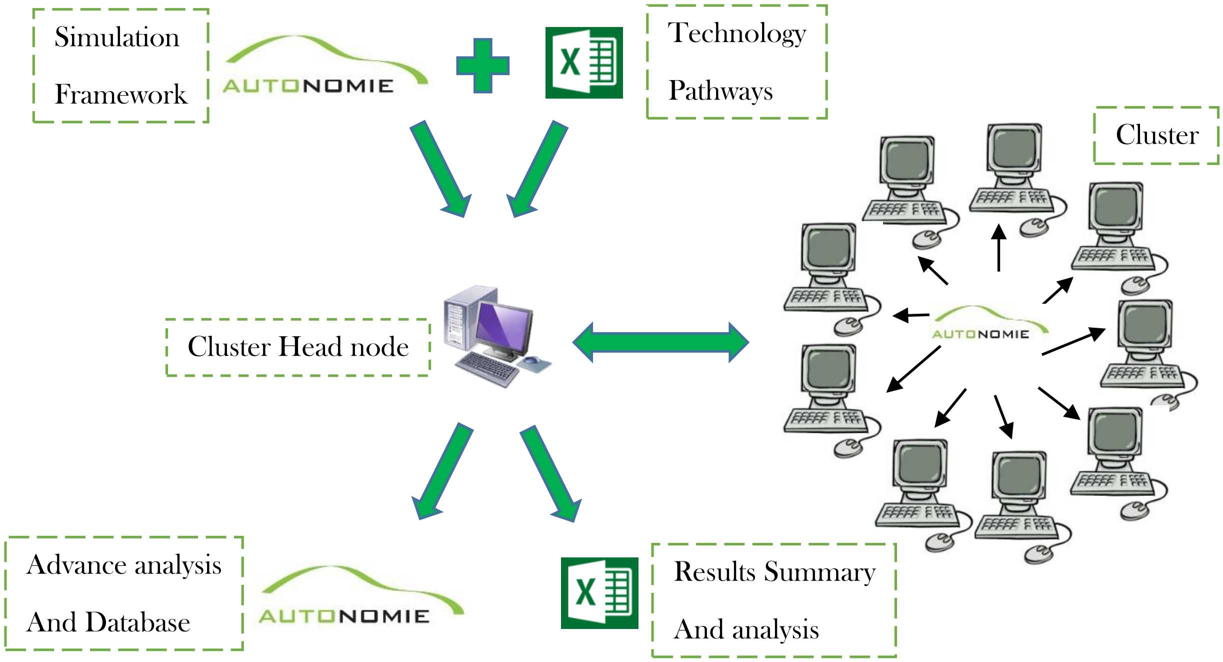


Figure 29 - Distributed Computing Process Diagram

8.2. Distributed Computing Flexibility

One of the biggest advantage of the distributed computing is that it also greatly facilitated the quick rerun of simulations, which will occurred numerous times during this study. This allowed Argonne to develop a new process: an ultimate Large Scale Simulation Process (LSSP) that is functional, smooth and flexible with the possibility to easily and quickly add and rerun as many vehicle as wanted, as many new technologies as needed making simulation in a very large number easier and faster than ever before.

For example, the second phase of the study will include 17 engine technologies when only 6 are currently simulated. The generic process will be able to automatically handle the additional technologies without any code modification. As a result, Volpe's future technological needs will be easily and quickly integrated to the process at any time and proceed to new runs in order to feed the model for CAFE rules.

9. Vehicle Sizing Process

9.1. Vehicle Technical Specification

In order to compare different vehicle technologies/configurations/powertrains, sizing the components to meet similar requirements is necessary.

All the vehicles have been sized to meet the same requirements:

- Initial vehicle movement (IVM) to 60 mph in 9 sec +/-0.1 sec
- Maximum grade (grade ability) of 6% at 65 mph at gross vehicle weight (GVW)
- Maximum vehicle speed >100 mph

These requirements are a good representation of the current American automotive market as well as American drivers' expectations. A relationship between curb weight and GVW was developed on the basis of current technologies to estimate the GVW of future technologies.

9.2. Component Sizing Algorithms

Owing to the impact of the component maximum torque shapes, maintaining a constant power-to-weight ratio between all configurations leads to an inconsistent comparison between technologies because of different performances. Each vehicle should be sized independently to meet the specific vehicle technical specifications presented previously.

Improperly sizing the components will lead to differences in fuel consumption and will influence the results. On this basis, we developed several automated sizing algorithms to provide a fair comparison between technologies. Different algorithms have been defined depending on the powertrain (e.g., conventional, power-split, series, electric) and the application (e.g., HEV, PHEV).

All algorithms are based on the same concept: the vehicle is built from the bottom up, meaning each component assumption (e.g., specific power, efficiency, etc.) is taken into account to define the entire set of vehicle attributes (e.g., weight, etc.). This process is always iterative in the sense that the main component characteristics (e.g., maximum power, vehicle weight, etc.) are changed until all vehicle technical specifications are met. On average, the algorithm takes between 5 and 10 iterations to converge. Figure 30 shows an example of the iterative process for a conventional vehicle.

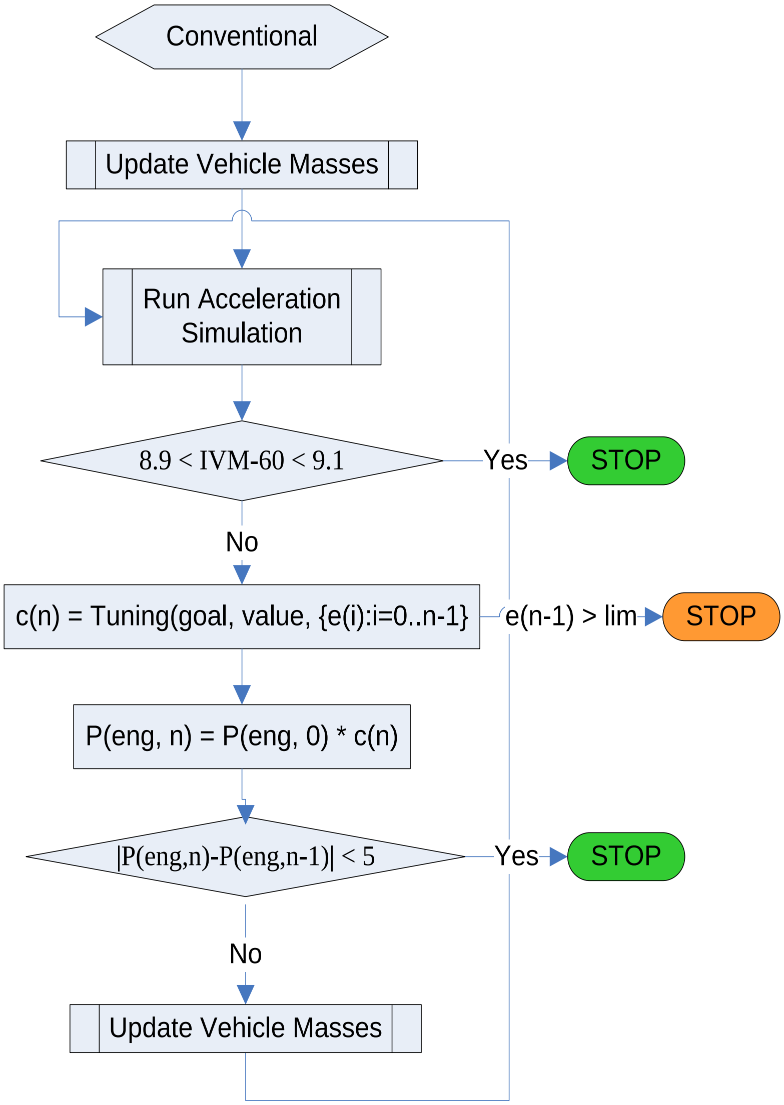


Figure 30 – Conventional-Powertrain Sizing Algorithm

Since each powertrain and application is different, the rules are specific:

- For HEVs, the electric-machine and battery powers are determined to capture all the regenerative energy from an FTP cycle. The engine and the generator are then sized to meet the grade ability and performance (IVM to 60 mph) requirements.
- For PHEV20s, the electric machine and battery powers are sized to be able to follow the FTP cycle in electric-only mode (this control is only used for the sizing; a blended approach is used to evaluate consumptions). The battery usable energy is defined to follow the FTP drive cycle for 20 miles, depending on the requirements. The engine is then sized to meet both performance and grade ability requirements (usually, grade ability is the determining factor for PHEVs).

- For PHEV40s, the main electric-machine and battery powers are sized to be able to follow the aggressive US06 drive cycle (duty cycle with aggressive highway driving) in electric-only mode. The battery usable energy is defined to follow the FTP drive cycle for 40 miles, depending on the requirements. The genset (engine + generator) or the fuel-cell systems are sized to meet the grade ability requirements.
- For BEVs, the electric machine and energy storage systems are sized to meet all the VTS.

The MHEV, BISG and CISG have very similar sizing results to their respective conventional as they all use the same sizing rule.

10. Vehicle Simulation Process

Once the vehicles are sized the meet the same Vehicle Technical Specifications, they are simulated following the appropriate standard driving cycles. After the simulations (11,940 vehicles or > 250,000 runs), it is important to properly store individual results as they will be reused to support the database generation (explained later on), that is why structured data is necessary.

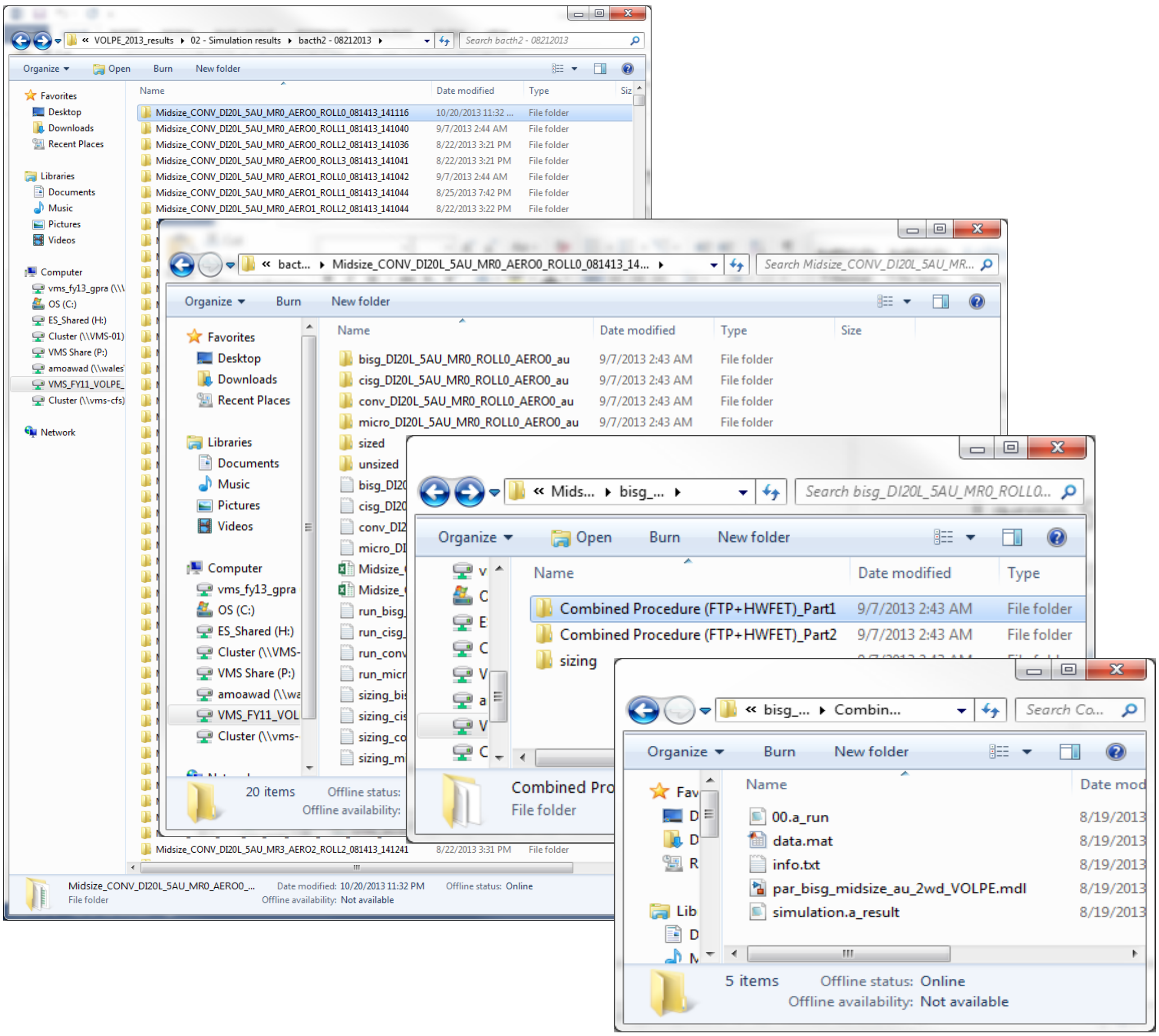


Figure 31 – Results Folder Organization for Individual Simulations

Figure 31 shows the folder organization for each individual simulation. Every folder contains the results for ONE specific combination, it characterizes one branch / one path of the tree. Each vehicle result folder could have up to 5 directories depending on the vehicle technology and the type of run performed. The results are divided into directories representing the cycle or procedure simulated. For example, the combined procedure for conventional vehicles has 2 parts separating the FTP and HFET run, the PHEV procedure has 4 parts separating the FTP and HFET runs as well as the Charge Sustaining and the Charge Depleting modes. The last directory is the sizing structure (performance test).

10.1. Run File

The “xx.a_run” is a copy of the vehicle concatenated to a cycle/procedure as shown in Figure 32. This file allows us to reproduce the simulation in the future if modifications or changes are to occur.

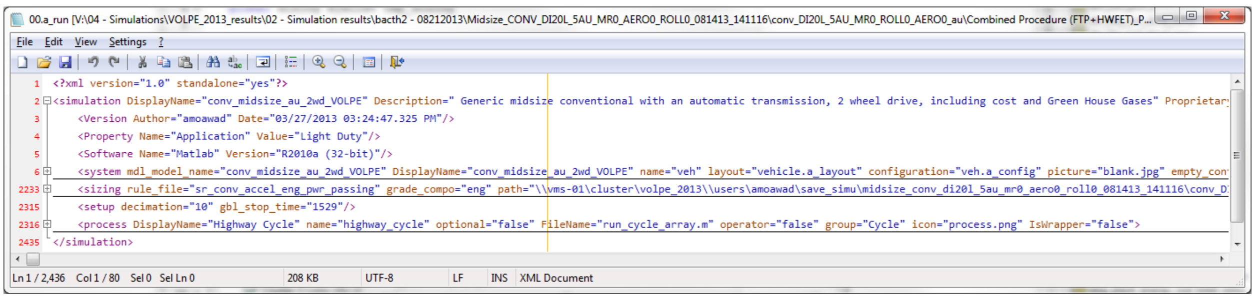


Figure 32 – Autonomie Run File

10.2. Data.mat File

The “data.mat” is the actual result file containing ALL the vehicle parameters and ALL the time based signals. A sample of signals and parameters included in the data.mat is shown in Figure 33.

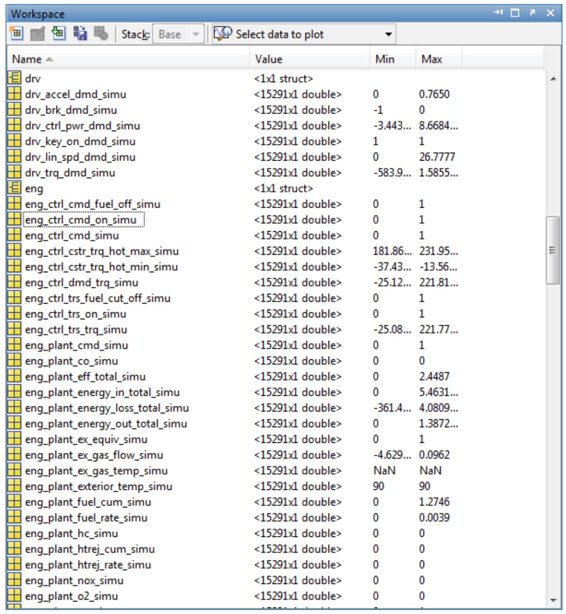


Figure 33 – Autonomie data,mat File

10.3. Vehicle Model

The “*.mdl” represents the complete vehicle model as shown ion Figure 34. Saving each specific vehicle model ensures that any simulation can be exactly rerun at any point in time.

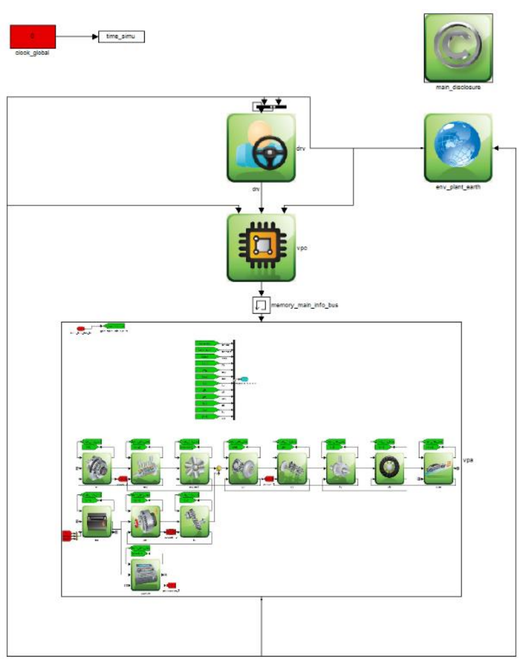


Figure 34 – Autonomie Conventional Vehicle

10.4. Results XML File

As shown in Figure 35, the “simulation.a_result” is an XML version of the actual result file that includes the main simulation inputs and outputs. This file will be later used to generate the complete MySQL database.

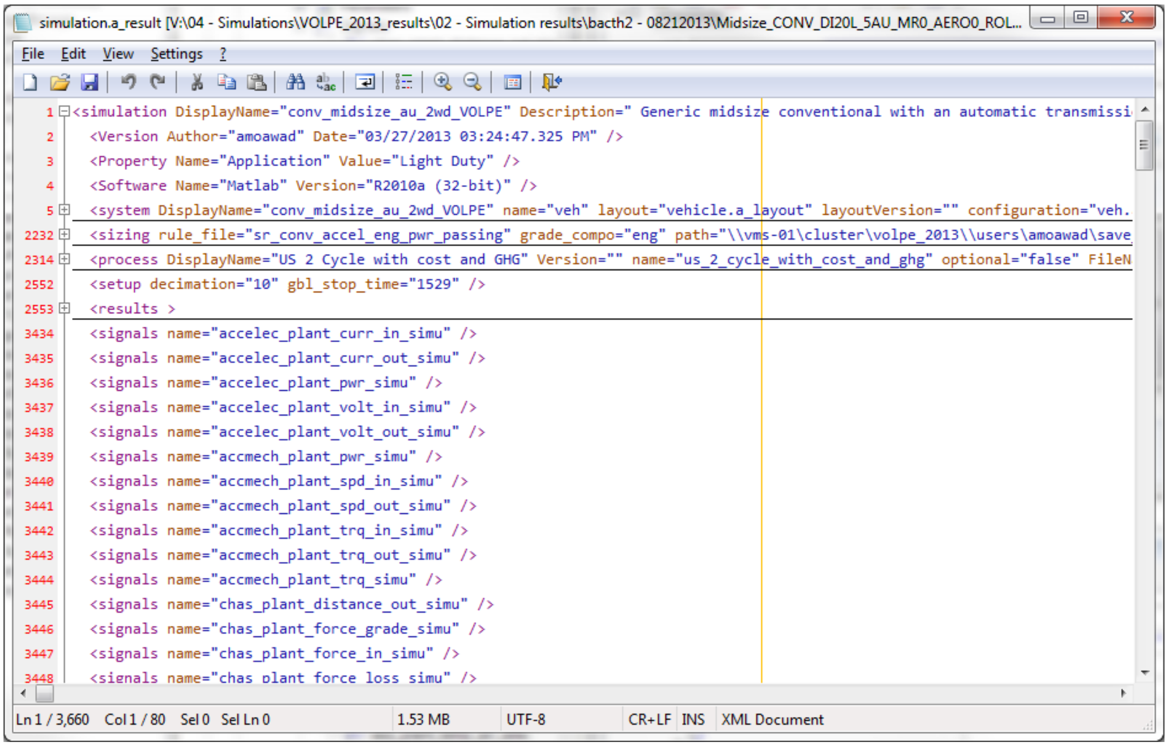


Figure 35 – Autonomie Results XML File

10.5. Folder Naming Nomenclature

The MySQL database that will be created and used by the VOLPE model needs to have a specific list of parameters to be able to search and retrieve the specific information of a particular vehicle. Since some of these parameters were not provided by Autonomie, a specific naming nomenclature was adopted for the folder name. Figure 36 shows and example of the folder naming nomenclature.

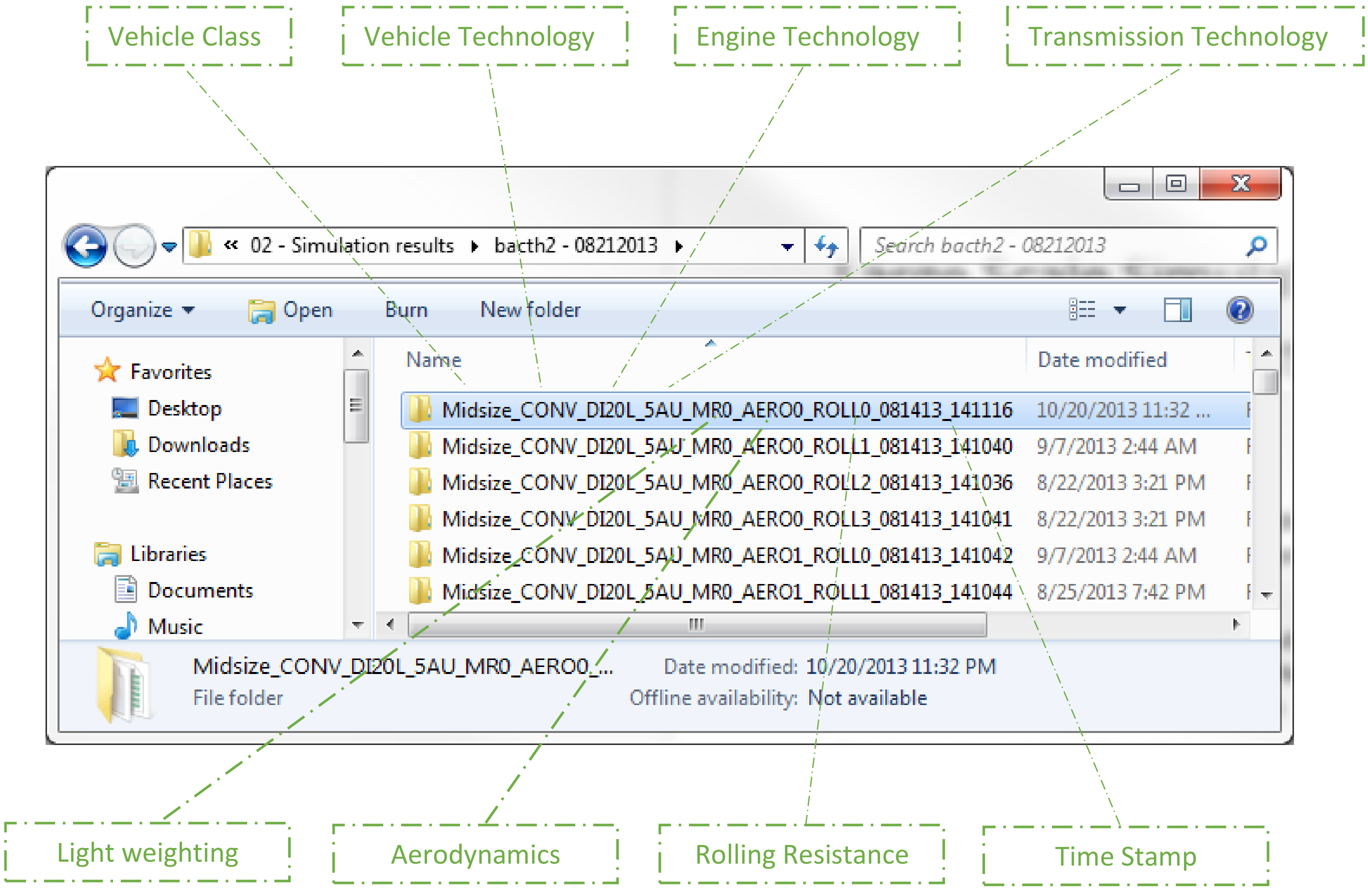


Figure 36 – Folder Naming Nomenclature

The naming convention are similar to the acronyms currently used in the decision trees by the VOLPE model. For example, the transmission technology acronyms are:

- 5AU ---- 5-speed Automatic Transmission
- 6AU ---- 6-speed Automatic Transmission
- 8AU ---- 8-speed Automatic Transmission
- 6DCT ---- 6-speed Dual Clutch Transmission
- 8DCT ---- 8-speed Dual Clutch Transmission
- 5DM ---- 5-speed Manual Transmission
- 6DM ---- 6-speed Manual Transmission
- 8DM ---- 8-speed Manual Transmission

The lighweighting acronyms are:

- MR0 ---- Glider Mass Reduction of 0%

- MR1 ---- Glider Mass Reduction of 1.5%
- MR2 ---- Glider Mass Reduction of 7.5%
- MR3 ---- Glider Mass Reduction of 10%
- MR4 ---- Glider Mass Reduction of 20%

The aerodynamics acronyms are:

- AERO0 ---- Aerodynamics Reduction of 0%
- AERO1 ---- Aerodynamics Reduction of 10%
- AERO2 ---- Aerodynamics Reduction of 20%

The rolling resistance acronyms are:

- ROLL0 ---- Rolling resistance Reduction of 0%
- ROLL1 ---- Rolling resistance Reduction of 5%
- ROLL2 ---- Rolling resistance Reduction of 10%
- ROLL3 ---- Rolling resistance Reduction of 20%

Since for that study, the engine technologies were not all represented, the following acronyms were selected as an intermediate step:

- PFI20L – 2.0 liter naturally aspirated engine, port fuel injection, variable valve timing
- DI20L ---- 2.0 liter naturally aspirated engine, variable valve timing, direct injection
- DIVVL20L ---- 2.0 liter naturally aspirated engine, variable valve timing, variable valve lift, direct injection
- TDI16L ---- 1.6 liter turbo charged engine, direct fuel injection, variable valve timing
- TDIVVL16L ---- 1.6 liter turbo charged engine, direct fuel injection, variable valve timing and lift
- TDIVVL12L ---- 1.2 liter turbo charged engine, direct fuel injection, variable valve timing

10.6. Individual Vehicle Validation

Once the simulation are completed, Autonomie provide the ability to analyze individual simulations both at a high level (i.e. fuel economy) and low level (i.e. time based engine power) through its Graphical User Interface. An algorithm is also used to automatically flag any potential issue within a simulation (i.e. too many shifting events on a specific cycle).

Figure 37 shows a sample of parameter outputs from Autonomie provided for every vehicle among the 11,940 vehicles simulated. In addition to Fuel Economy, Autonomie provides also other electrical consumption, component efficiencies, component power, etc… The list of output parameter generated for the Volpe model is detailed later in the report.

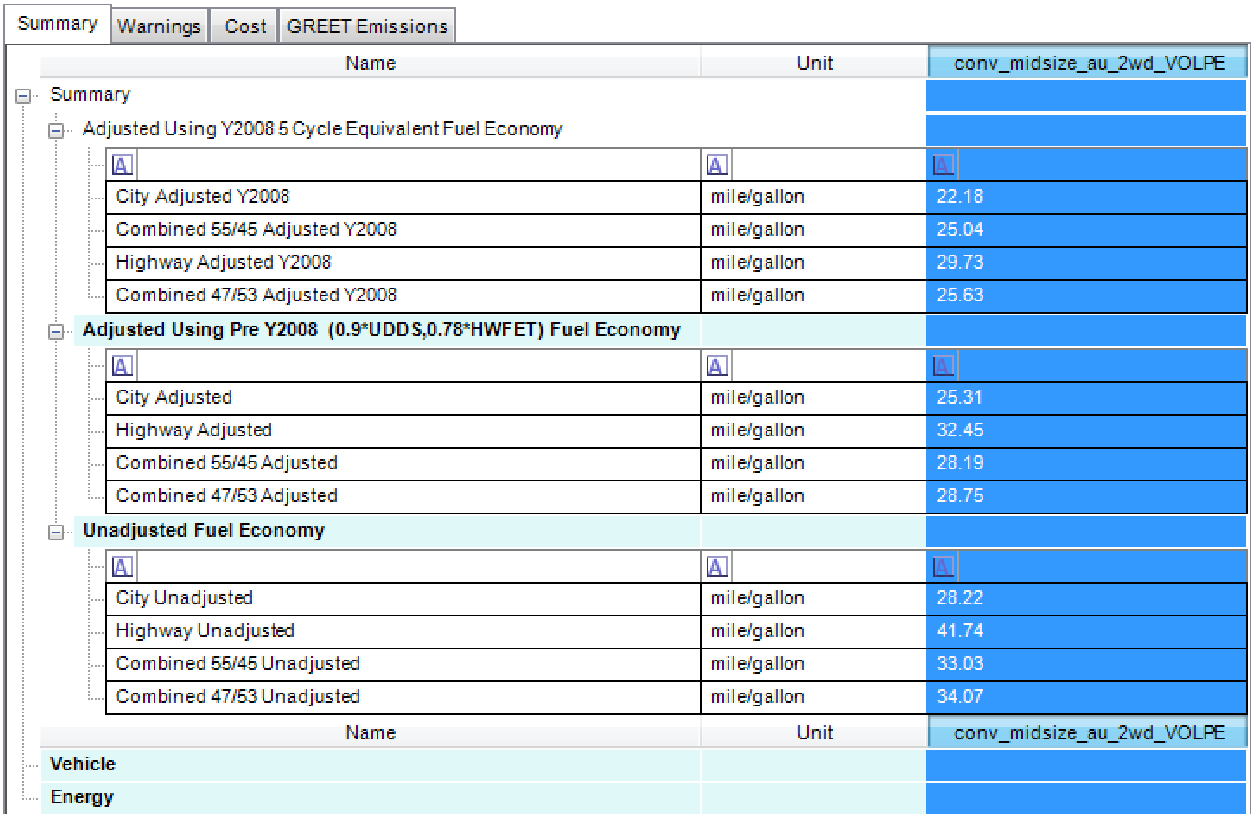


Figure 37 – Baseline Conventional Vehicle Outputs

Numerous pre-defined plots are also available to analyze any time based parameter from the simulation. Figure 38 shows an example of engine speed, vehicle speed and gear number for a conventional vehicle.

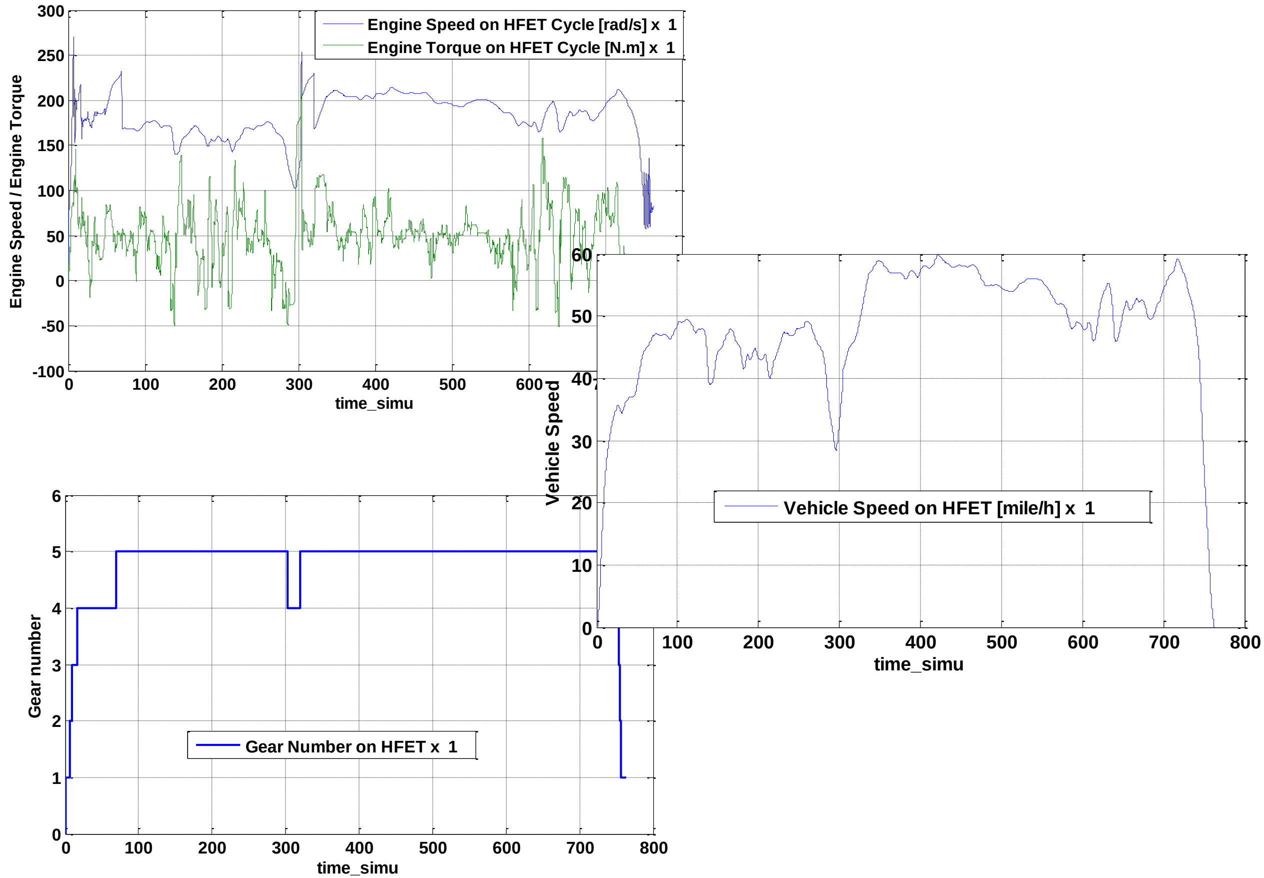


Figure 38 - Engine Speed, Engine torque, Gear Number and Vehicle Speed time based signals on HFET Cycle

11. Vehicle Database

VOLPE model requirements require the user to tackle two complicated problems simultaneously:

- A vehicle simulation tool must be used to quickly and properly estimate energy consumption of a very large number of specific vehicle, powertrain and component technologies.
- The user must easily access and analyze information across large amounts of data.

As discussed previously, a specific process has been designed to perform large scale simulation with Autonomie. Using Autonomie, a simulation can be quickly validated to ensure correct results and discrepancies in the results can be examined in details. Additionally, Autonomie is fully integrated with distributed computing, making extremely large numbers of simulations, such as the quantity required for full VOLPE analysis, feasible.

However, Autonomie was not initially designed to provide data analysis capabilities across such large sets of data. The requirements for this type of analysis are much different than those designed for individual simulation analysis. In particular, such analysis imposes data management concerns (number of files, disk size, access time, etc.), running post-processing calculations without the time cost of rerunning all of the simulations, and plots, calculations, and other analysis tools for looking at high level indicators and spotting of overall trends.

In order to support this second critical piece, Argonne has developed a new process that allows the detailed simulation results provided by Autonomie to be distilled into a format that can be easily distributed and analyzed horizontally, across many simulations, rather than a deep, vertical dive into one simulation. Both aspects are critical (and necessary) for the full scale vehicle analysis that VOLPE requires.

As mentioned before, the output of the simulations includes everything necessary for Autonomie to analyze or recreate an individual simulation, including the Simulink model representing the vehicle, a metadata file containing simulation results *.a_result file and a data.mat file containing all the time-based, signal data. These results can be archived for full traceability and reproducibility of all simulations.

However, it is not feasible to share or analyze this data. For example, 7,503 simulation results resulted in 296 GB of disk space usage. It's simply not scalable to pass this much information around, much less the number of simulations required for VOLPE. Additionally, each simulation has individual files storing the results, so just managing or indexing the sheer number of files becomes an issue. However, most of the information contained in those result files is unnecessary for the VOLPE analysis (i.e. second by second fuel or electrical consumption values).

11.1. Database Creation

Argonne's database creation process takes an input sheet which specifies which parameters (input or output) should be included in the database. The process will look through all of the simulation result files, extract the specified parameters, and store them in a single, specialized database file. This allows us to exclude irrelevant information not needed for cross-cutting simulation analysis, while leaving the full results archived, just in case. Figure 39 lists the input and output parameters currently included in the database.

INPUT

- Vehicle Name
- Vehicle Class
- Mass Reduction
- Electric Range
- Rolling Resistance
- Aerodynamics
- Powertrain Type
- Engine Type
- Transmission type
- Fuel Type
- Battery Type

OUTPUT

- Engine Power
- Fuel Cell Power
- Motor1 Power
- Motor2 Power
- Battery Usable Energy
- Vehicle Mass
- FTP Fuel Consumption
- FTP Electrical Consumption
- HFET Fuel Consumption
- HFET Electrical Consumtpion
- Combined Fuel Consumption
- Combined Electrical Consumption

AUTONOMIE PROCESS

Figure 39 – Inputs and Outputs from Simulation can be saved to the Database

A single database file is easy to redistribute. The aforementioned 296 GB of data compressed down into 30.4 MB of data, and took only 27 minutes to generate from the original simulation results. Additionally, the database is developed using the MS SQL Express 2012 format, which is free and easily accessed by standard SQL tools and queries.

11.2. Database Structure

As shown in Figure 40, the database is structured to be generic, so that any simulation input parameter, result, or descriptive property can be stored. This allows the maximum flexibility in the type of data which can be stored. The tables are structured to allow logical grouping of data, maximize retrieval speed, and minimize disk space.

Vehicles and the references to their parameters are stored separately from parameters specific to the type of simulation, because the same vehicle can be run on multiple procedures or cycles. For example, one vehicle may be run on an acceleration test and also a fuel consumption test, such as a combined cycle procedure. Each simulation may produce a fuel consumption, which would then be linked to that simulation record. However, parameters common across both simulation runs, such as the coefficient of drag of the vehicle, would be linked to the vehicle record. Not all vehicles and simulations have the same parameters, for example, motor parameters are only available for a vehicle with an electric power path (e.g. EVs, HEVs, PHEVs), and fuel consumption is only available for simulations with an engine or fuel cell (i.e. not EVs).

Each parameter stores name, description, data type (i.e. string, double, integer, Boolean), and unit. The values themselves are organized into tables by data type for disk size optimization.

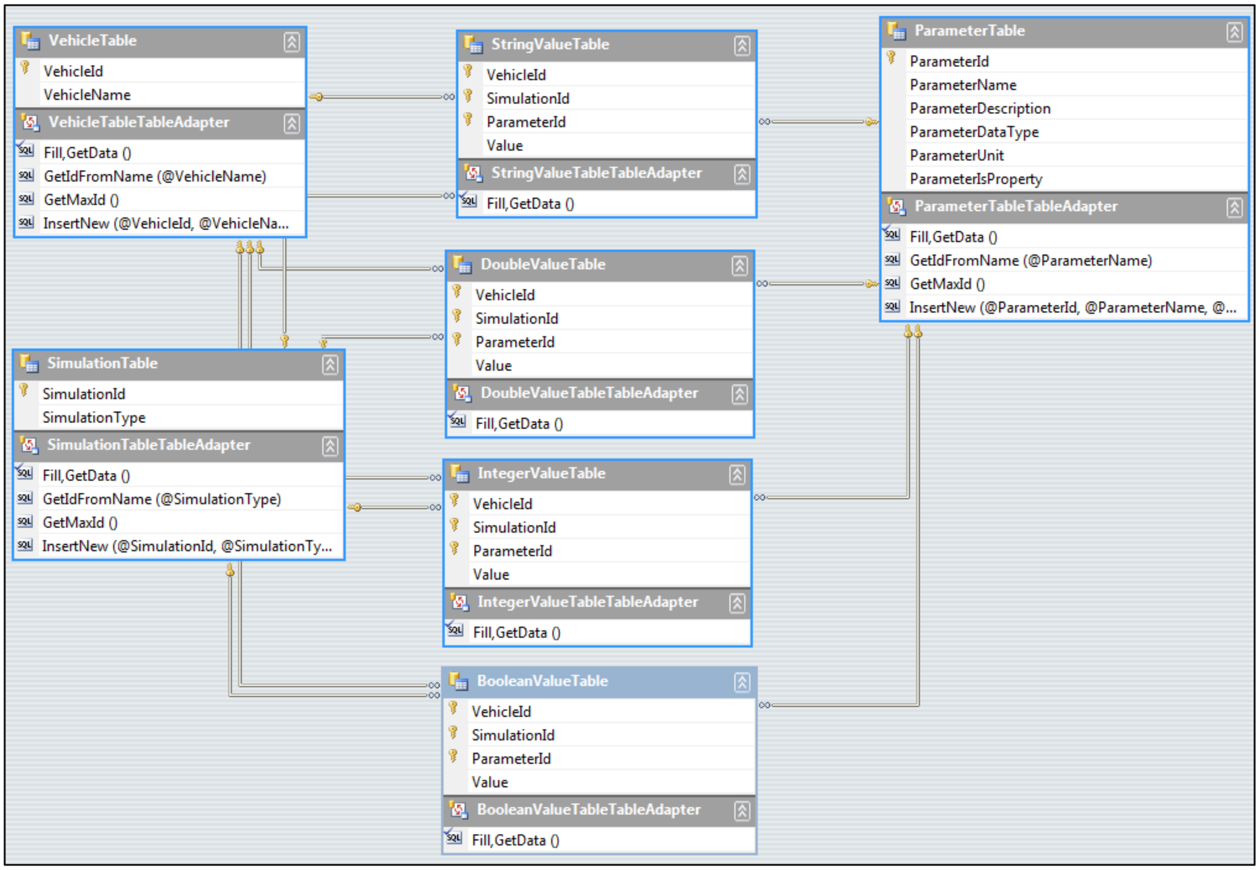


Figure 40 - Database Structure

11.3. User Interface

Although the database is accessible by any tool or programming language which can interact with databases, Argonne has also developed an analysis tool to easily visualize and analyze the data (Figure 41). This tool provides a quick and intuitive way for users to quickly select subsets of simulation results of interest, select which parameters to view, modify assumptions, perform additional post processing calculations on the data retrieved from the database, and view plots to better visualize the data.

Additionally, the user interface provides some advanced features that allow users to import their own plots and analysis functions, save "projects" of filters, parameters, and overridden assumptions, or export subsets of the data to Excel for additional data analysis or redistribution.

This tool allows users who are not familiar or comfortable with direct database access to perform the analysis necessary for VOLPE.

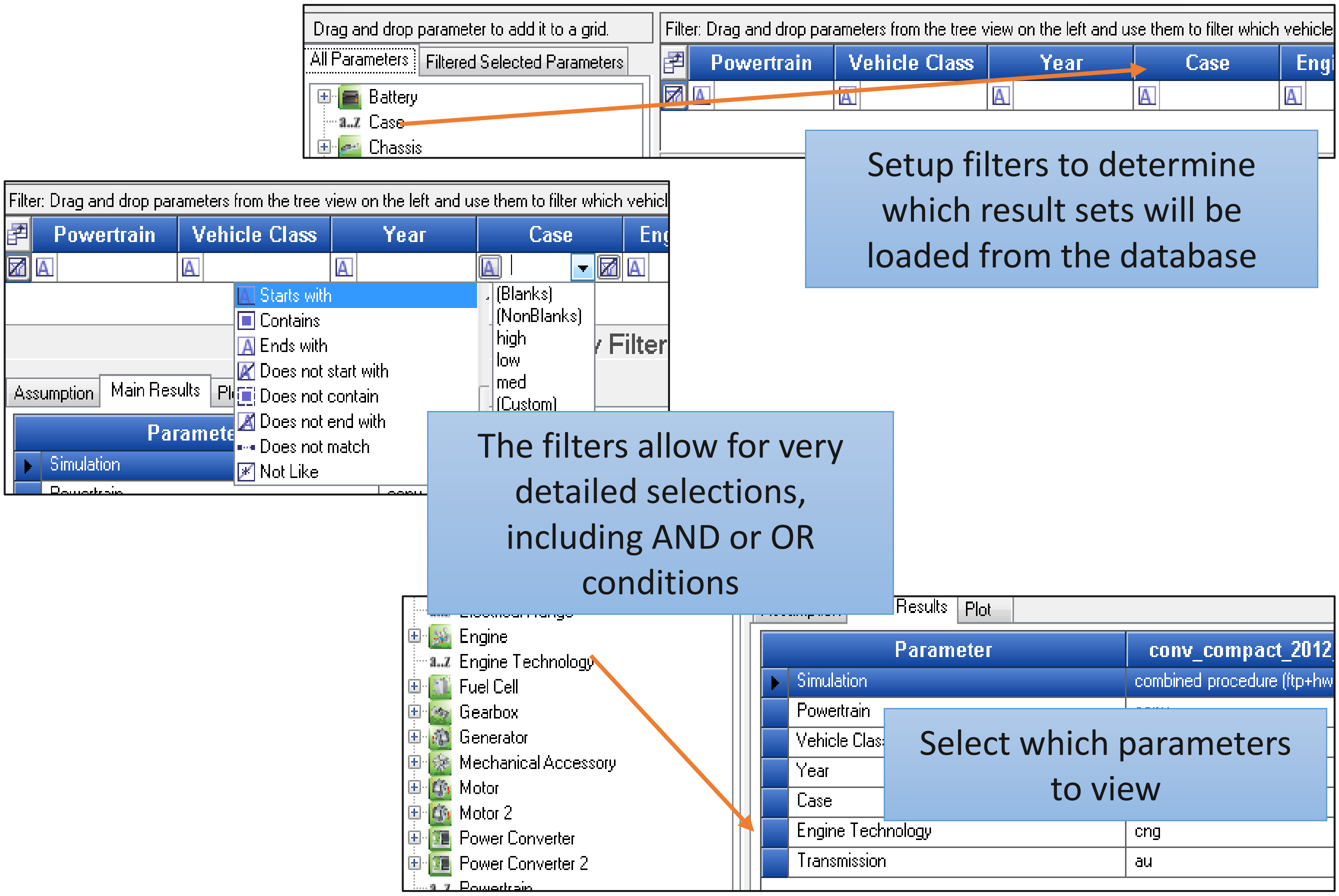


Figure 41: Database Analysis Tool

11.4. VOLPE Model Access to the Database

A critical part of the process validation was to ensure that the VOLPE model can access any information from the database. That step was successfully validated by the VOLPE developers using a complete my SQL database provided by Argonne.

12. Reducing the Number of Simulation through Statistical Analysis

One approaches' to accelerate the simulation time is to use distributed computing as previously mentioned. Another one is to use statistical analysis to down select the number of simulations to be run and develop an algorithm to populate the complete database from a subset of simulations using the statistical analysis.

As previously stated, the Math and Computer Science (MCS) division at Argonne collaborated with the System Modeling and Control group in order to develop a method to minimize the number of runs required to fulfill Volpe's demand. The motivation was fueled by the fact that several of the technological improvements were linear. As a matter of fact, it was expected to find apparent relationships and trends especially linked to weight reduction, aerodynamics as well as rolling resistance. In order to minimize the numbers of simulations/combinations, MCS has defined the relationships between component technologies to minimize the number of simulations.

12.1. List of Inputs and Outputs

To perform the analysis, a complete set of simulation results including the list of all the input and outputs required by the VOLPE model was provided to MCS. The idea is that once the relationships are created, one would not have to run the complete set of simulations anymore.

Figure 42 and Figure 43 show the inputs and outputs provided for the analysis. Column A to L characterize the inputs, Column M to W characterize the output. Each row presents one vehicle.

	A	B	C	D	E	F	G	H	I	J	K	L
1	Vehicle Name	Vehicle Class	Glider Mass	Electric Range	Mass Reduction	Aero	Rolling	Powertrain	Engine	Fuel	Battery	Transmission
2	bisg_DI20L_5AU_MR0_ROLL0_AERO0_au	Midsize	1000	0	MR0	AERO0	ROLL0	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
3	bisg_DI20L_5AU_MR0_ROLL0_AERO1_au	Midsize	1000	0	MR0	AERO1	ROLL0	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
4	bisg_DI20L_5AU_MR0_ROLL0_AERO2_au	Midsize	1000	0	MR0	AERO2	ROLL0	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
5	bisg_DI20L_5AU_MR0_ROLL1_AERO0_au	Midsize	1000	0	MR0	AERO0	ROLL1	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
6	bisg_DI20L_5AU_MR0_ROLL1_AERO1_au	Midsize	1000	0	MR0	AERO1	ROLL1	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
7	bisg_DI20L_5AU_MR0_ROLL1_AERO2_au	Midsize	1000	0	MR0	AERO2	ROLL1	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
8	bisg_DI20L_5AU_MR0_ROLL2_AERO0_au	Midsize	1000	0	MR0	AERO0	ROLL2	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
9	bisg_DI20L_5AU_MR0_ROLL2_AERO1_au	Midsize	1000	0	MR0	AERO1	ROLL2	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
10	bisg_DI20L_5AU_MR0_ROLL2_AERO2_au	Midsize	1000	0	MR0	AERO2	ROLL2	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
11	bisg_DI20L_5AU_MR0_ROLL3_AERO0_au	Midsize	1000	0	MR0	AERO0	ROLL3	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
12	bisg_DI20L_5AU_MR0_ROLL3_AERO1_au	Midsize	1000	0	MR0	AERO1	ROLL3	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
13	bisg_DI20L_5AU_MR0_ROLL3_AERO2_au	Midsize	1000	0	MR0	AERO2	ROLL3	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
14	bisg_DI20L_5AU_MR1_ROLL0_AERO0_au	Midsize	985	0	MR1	AERO0	ROLL0	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
15	bisg_DI20L_5AU_MR1_ROLL0_AERO1_au	Midsize	985	0	MR1	AERO1	ROLL0	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU
16	bisg_DI20L_5AU_MR1_ROLL0_AERO2_au	Midsize	985	0	MR1	AERO2	ROLL0	Mild Hybrid BISG	DI20L	Gasoline	Liion	5AU

Figure 42 –Simulation Inputs for MCS

	M	N	O	P	Q	R	S	T	U	V	W
1	Engine Power	Fuel Cell Power	Motor Power	Motor 2 Power	Battery Power	Battery Usable Energy	Vehicle Mass	UDDS Fuel Consumption	UDDS Elecitrcal Consumption	HWFET Fuel Consumption	HWFET Electrical Consumption
2	134562	0	7000	0	0	0	1561	6.60E-05		4.94E-05	
3	133965	0	7000	0	0	0	1560	6.51E-05		4.76E-05	
4	133515	0	7000	0	0	0	1560	6.41E-05		4.58E-05	
5	134323	0	7000	0	0	0	1561	6.54E-05		4.89E-05	
6	133874	0	7000	0	0	0	1560	6.45E-05		4.71E-05	
7	133277	0	7000	0	0	0	1560	6.36E-05		4.54E-05	
8	134084	0	7000	0	0	0	1560	6.48E-05		4.84E-05	
9	133635	0	7000	0	0	0	1560	6.40E-05		4.66E-05	
10	133184	0	7000	0	0	0	1560	6.31E-05		4.49E-05	
11	133754	0	7000	0	0	0	1560	6.38E-05		4.75E-05	
12	133304	0	7000	0	0	0	1560	6.30E-05		4.57E-05	
13	132706	0	7000	0	0	0	1560	6.20E-05		4.39E-05	
14	133249	0	7000	0	0	0	1545	6.57E-05		4.92E-05	
15	132653	0	7000	0	0	0	1545	6.48E-05		4.74E-05	
16	132202	0	7000	0	0	0	1544	6.38E-05		4.57E-05	

Figure 43 - Simulation Output for MCS

The table below gives details of each column, the parameter name/description and the unit.

Table 4 – List of Parameters for MCS

COLUMN	**PARAMETER**	**UNIT**
Column A	Vehicle Name	No Unit
Column B	Vehicle Class	No Unit
Column C	Glider Mass	Kg
Column D	Electric Range	Miles
Column E	Mass Reduction Step	No Unit
Column F	Aerodynamics Reduction	No Unit
Column G	Rolling Resistance Reduction	No Unit
Column H	Vehicle Powertrain	No Unit
Column I	Engine Type	No Unit
Column J	Fuel Type	No Unit
Column K	Battery Type	No Unit
Column L	Transmission Type	No Unit
Column M	Engine Power	Watt
Column N	Fuel Cell Power	Watt
Column O	Motor 1 Power	Watt
Column P	Motor 2 Power	Watt
Column Q	Battery Power	Watt
Column R	Battery Useable Energy	Watt-Hour
Column S	Vehicle Mass	Kg
Column T	FTP Fuel Consumption	Liter/meter
Column U	FTP Electrical Consumption	Joule/meter
Column V	HFET Fuel Consumption	Liter/meter
Column W	HFET Electrical Consumption	Joule/meter

12.1. Exploratory Data Analysis

This section present an overview of the exploratory data analysis performed on the vehicle simulation results. The analysis comprises three phases: (i) correlation studies; (ii) sensitivity analysis; and (iii) predictive modeling. The preliminary analysis shows that for a given class of vehicles, several outputs from the vehicle simulation are highly correlated and 50% of the simulation runs can be reduced using state-of-the-art machine learning approaches.

12.1.1. Correlation Studies

First, we reduced the dimensionality of the output space by eliminating outputs that are highly correlated with one other output. Given two outputs, we computed the linear correlation between them. Using the Pearson product-moment correlation coefficient. Using this correlation measure, when an output *yp* is correlated to an output *yq* we remove *yq.*

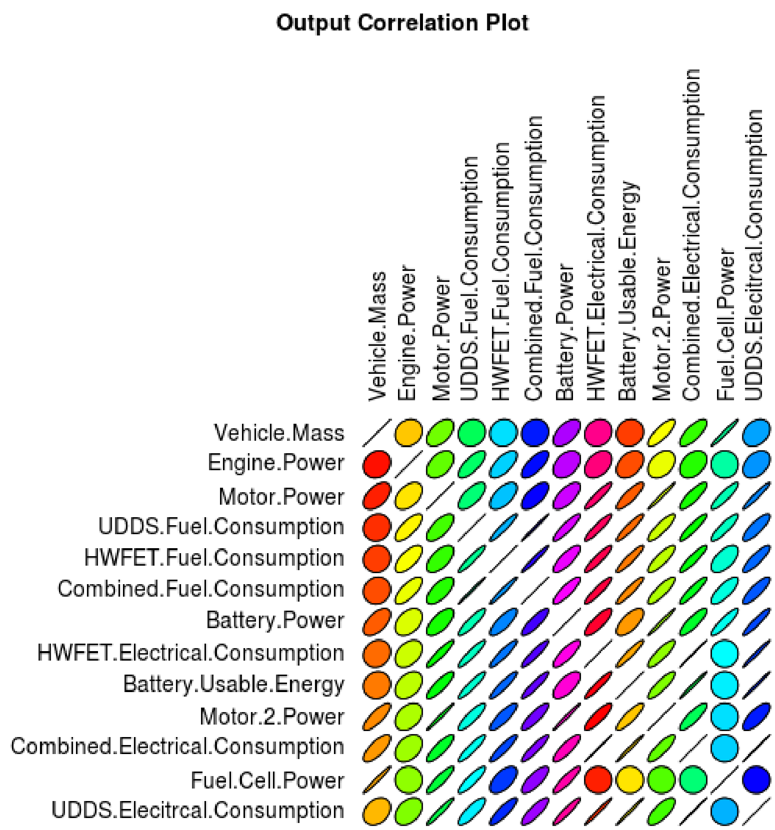


Figure 44 - Pairwise correlations among outputs. Each entry in the matrix represents the correlation measure between the corresponding entries. Circles and slanting lines denote no correlations and high correlations, respectively

Figure 44 shows the pairwise correlations between outputs. We observe that several outputs are highly correlated and that five outputs (Vehicle.Mass, Engine.Power, Motor.Power, Combined.Fuel.Consumption, and HWFET.Electrical.Consumption) are uncorrelated with the rest. Consequently, given the five outputs, the remaining eight outputs can be predicted. Therefore, we removed the eight correlated outputs from further analysis.

12.1.2. Sensitivity analysis

Next, we reduced the dimensionality of the input space by analyzing the impact of the input parameters on the uncorrelated outputs. For this purpose, we used the random forest method, a state-of-the-art machine learning approach. It is an ensemble learning method that operates by constructing a large number of decision trees at training time. For an unseen input, each tree predicts a value of the desired output and the final output of the model is an average over all the trees. In the training phase of the random forest, we randomly sample 50% of the data. The random forest model is fit on this training set. The mean squared error (MSE) on the training set is computed as follows:

$$\mathrm{MSE} = \frac{1}{l}\sum_{i=1}^{l}(f(x_i) - \hat{f}(x_i))^2, \tag{1}$$

where *l* is the number of training points, and *f*(*xi*) and *f^(xi*) are the observed value from the vehicle simulation and predicted value from the random forest model at the input parameter configuration *xi*, respectively. To assess the impact of an input parameter *m*, the values of *m* in the training set are randomly permuted. Again, a random forest model is fit on this imputed training set and the mean squared error is computed. This procedure is repeated for a number of times. If a parameter *m* is important, permuting the values of *m* should affect the prediction accuracy significantly resulting an increase in the MSE. For each parameter *m*, the percentage increase in MSE (%IncMSE) will allow us to assess the importance of the parameter *m*. A permutation example is shown below. To assess the importance of the first parameter in the training set represented by the matrix **T**, we permute the values of the first column (that corresponds to the values of the first parameter) in the matrix, which is shown in **T′1**.

$$\mathbf{T} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 2 & \cdots & \cdots \\ 3 & \ddots & \vdots \\ 4 & \cdots & \cdots \end{bmatrix} \qquad \mathbf{T'}_1 = \begin{bmatrix} 4 & \cdots & \cdots \\ 2 & \ddots & \vdots \\ 3 & \cdots & \cdots \end{bmatrix}$$

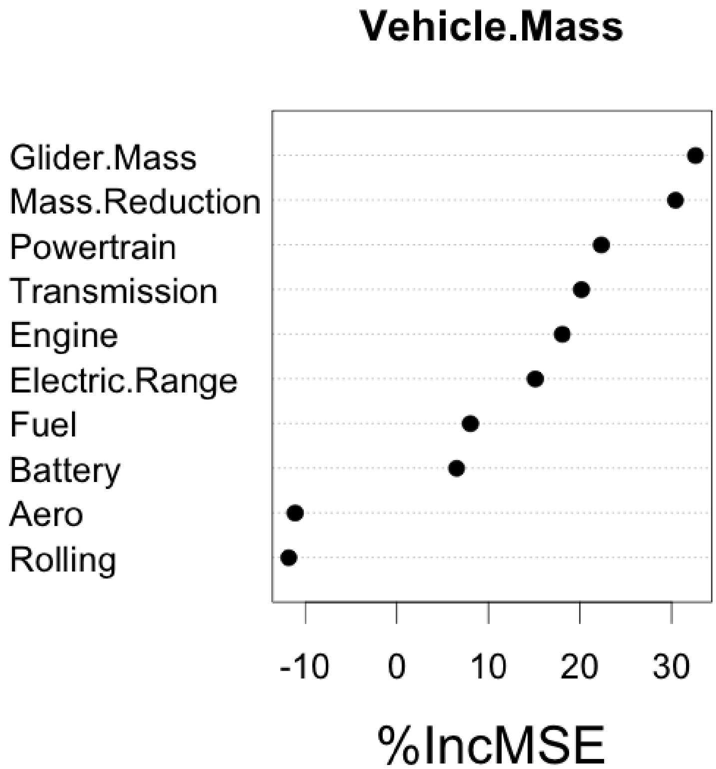


Figure 45 – Impact of each input on Vehicle.Mass measured across the testing set

For the output Vehicle.Mass, Figure 45 shows the %IncMSE for each input parameter. We observe that input parameters Glider.Mass, Mass.Reduction, and Powertrain have a significant impact on Vehicle.Mass but Aero and Rolling are insignificant. Note that the negative %IncMSE is an artifact of over fitting the random forest model.

Using this analysis, for each uncorrelated output, we remove inputs that do not have a significant impact on the corresponding output.

12.1.3. Predictive Modeling

For each uncorrelated output, we can now build a predictive model using the random forest method. We estimate the number of training points (simulation runs) required to obtain high prediction accuracy. Given *Nyp* observed data points for the output *yp*, we sample *k*% of the *Nyp* points at random for training and we use the remaining points for testing. As an accuracy measure, we compute the root mean squared error (RMSE = √MSE) on the test set. To reduce the randomness due to random sampling and the random forest method, we repeat the experiments 10 times.

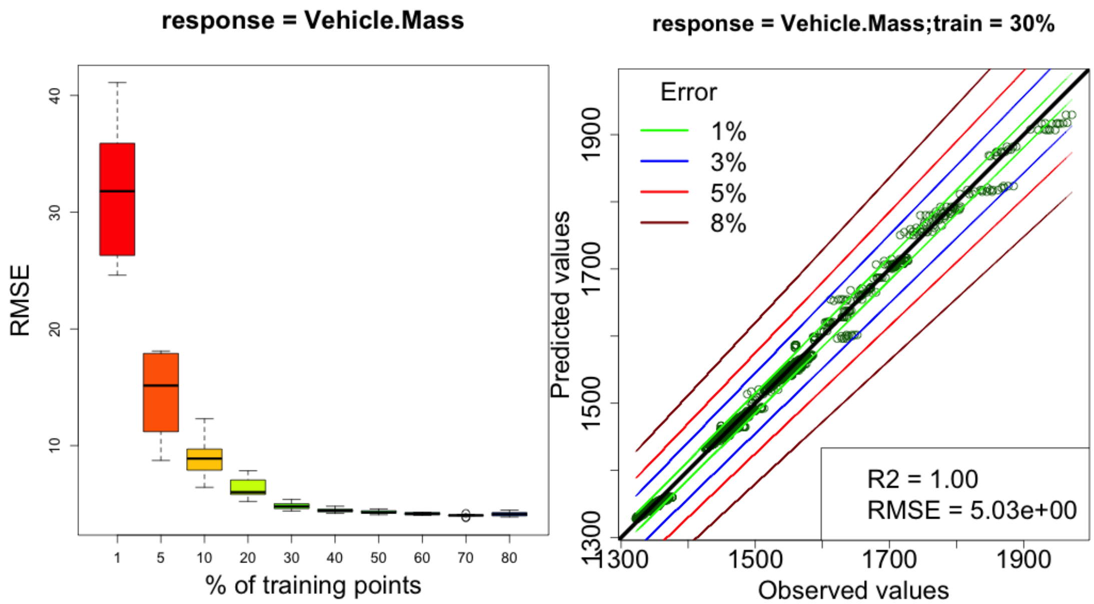


Figure 46 – Predictive modeling for Vehicle.Mass. Root mean squared error as a function of the % training points (left) obtained over 10 repetitions. Correlation between observed and predicted values when 30% of the simulation runs are used for training (right)

For illustration, we first focus on Vehicle.Mass, where Nyp = 11,490. Figure 46 (left) shows the box plots of the RMSE obtained over 10 repetitions for various numbers of training points. We observe that with 30% of the points used for training, the random forest method can reach high prediction accuracy. Further increases in the number of training points do not reduce the RMSE significantly. For training points, Figure 46 (right) shows the correlation between the observed and the predicted values along with the error bound computed on the observed values. The results indicate that the errors in the predicted values are within ±3% of the observed values (the blue line). For the remaining 4 uncorrelated outputs, the required number of training points ranges between 20% (with ±5% error for Motor.Power) and 50% (with ±8% error for Combined.Fuel.Consumption—see Figure 47).

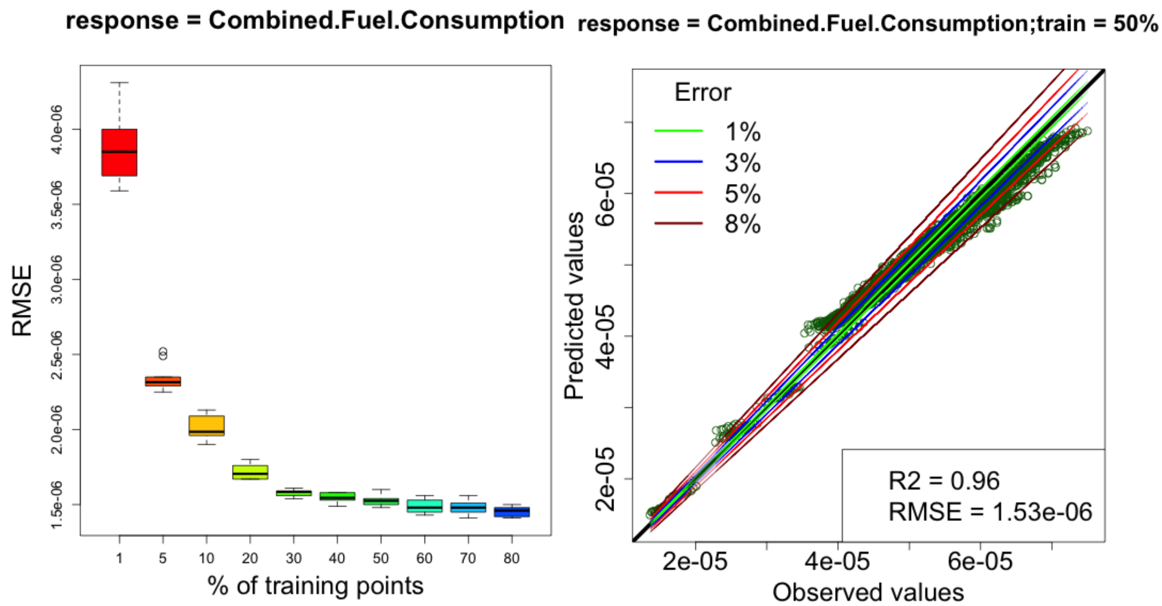


Figure 47 – Predictive modeling for Combined.Fuel.Consumption. Root mean squared error as a function of the % training points (left) obtained over 10 repetitions.

13. Conclusion

The objective of the project was to develop and demonstrate a process to replace the current decision trees and synergies by individual results generated from detailed vehicle simulations.

This report described the process developed including the generation of the MySQL database that will be accessible by the VOLPE model. The process was validated by running a very large number of simulations representing most of the vehicle, powertrain and component technologies currently included in the decision trees.

Next steps will focus on

- Integrating the remaining component technologies that were not initially modeled due to the lack of data (i.e. engine technologies)
- Run the complete set of simulations and validate the results
- Improving the process (i.e. limiting the number of simulation runs using the statistical analysis approach, accelerating the simulation time, enhance the process to automatically check the simulation results…)
- Verifying that all the required parameters by the VOLPE model are included in the database
- Modify the VOLPE model to extract the required parameters from the new database rather than use the decision trees and synergies.